Technical Note N- 1134

THE SPHERICAL ACRYLIC PRESSURE HULL FOR HYDROSPACE APPLICATION: PART IV - CYCLIC FATIGUE OF NEMO CAPSULE #3

By

J. D. Stachiw

October 1970

NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California 93041

THE SPHERICAL ACRYLIC PRESSURE HULL FOR HYDROSPACE APPLICATION: PART IV
CYCLIC FATIGUE OF NEMO CAPSULE #3

Technical Note N-1134

YF 38.535.005.01.006

by

J. D. Stachiw

ABSTRACT

The 66-inch outside diameter 2.5-inch thick NEMO Model 600 spherical hull #3 has been hydrostatically pressure cycled till fatigue cracks appeared in the acrylic plastic and the top hatch plastically buckled. The plastic buckling of the hatch, fabricated from annealed 4130 alloy steel, took place during simulated repeated dives in the 2080 to 2250 foot depth range. The cracks in the acrylic plastic hull were located in the beveled surface in contact with the metallic polar closures. The first crack was observed only after the hull had been subjected to 993 consecutive pressure cycles, of which 815 cycles were to 1200 feet followed immediately by 178 cycles to 1540 feet. An additional 257 pressure cycles to 2080 foot depth did not implode the pressure hull but only caused the cracks to extend further into the hull. The duration of sustained pressure loading in each pressure cycle was approximately 45 minutes followed by 45 minute relaxation period.

The cyclic tests conclusively prove that (1) an adequate cyclic fatigue safety factor exists for NEMO hulls performing, routinely, extended manned dives to 600-foot depth, and that (2) manned proof test dives of 1 hour duration to 1200-foot depth can be performed providing the total number of proof test dives does not exceed 100. To prevent plastic buckling of the polar steel closures prior to general implosion of the capsule it is necessary to specify heat treated 4130 steel alloy for the polar penetration closures.

BLANK PAGE

INTRODUCTION

The Naval Civil Engineering Laboratory, under sponsorship of the Naval Facilities Engineering Command, has completed[1] in 1969 the successful development of spherical acrylic plastic pressure hull NEMO* Model 600 for manned exploration of continental shelf depths. These hulls have a 66-inch outside diameter (D), 2.5-inch wall thickness (t), are equipped with two metallic penetration closures located at the top and bottom poles of the sphere, and utilize bonded spherical pentagon modules for construction of the hull.

The prototype hull #0 of the NEMO Model 600 series has been tested to destruction after 107 pressure cycles in which its behavior under short-term and long-term hydrostatic loadings was evaluated.[1,2,3] The 4150-foot implosion depth of the NEMO Model 600 hull #0 proved that the 600-foot depth operational rating given to the NEMO Model 600 hulls is sufficiently safe for manned operation.

Two questions, however, remained that needed further elucidation. It was not known at what depth plastic buckling of the annealed 4130 steel alloy hatches would occur and it remained to be proven that the fatigue data generated by testing of 15-inch NEMO models was applicable to the full-scale NEMO hull. To answer these two questions, it was decided to pressure cycle a full-scale NEMO Series 600 hull until significant cracks occurred in the acrylic material and plastic buckling of the metallic penetration closures took place.

TEST SPECIMEN

NEMO Model 600 hull #3 served as the test specimen (Figure 1). The construction of hull #3 (Tables 1 and 2) was very similar (Figures 2 through 8) to that of hull #0 imploded previously[1] at 4150-foot depth during the full-scale NEMO hull development tests. The only significant difference between hull #3 built by Swedlow Inc. together with hulls #1 and #2 (Appendix A) and hull #0 built by the Pacific Missile Range was the use of different adhesive and steel alloy for the polar penetration closures (Figure 8).

Instead of PS-18 adhesive, hull #3 utilized SS-6217 adhesive developed by Swedlow Inc. The SS-6217 adhesive was especially formulated for this application to permit slower polymerization which resulted in almost complete absence of air bubbles in the bonded joint. The average tensile strength of the SS-6217 adhesive filled joints in hull #3 was 8300 psi with 8640 psi maximum and 6860 psi minimum strength. The 8300 psi average tensile strength of SS-6217 adhesive compared very favorably with the 9220 psi maximum, 5680 psi minimum and 7350 psi average strength established[1] for PS-18 adhesive in hull #0.

The polar penetration closures were fabricated from annealed 4130 alloy steel instead of type 316 stainless steel used in hull #0. The substitution of annealed 4130 alloy steel for 316 stainless steel was prompted by economy. Application of corrosion resistant plating to 4130

*Naval Experimental Manned Observatory

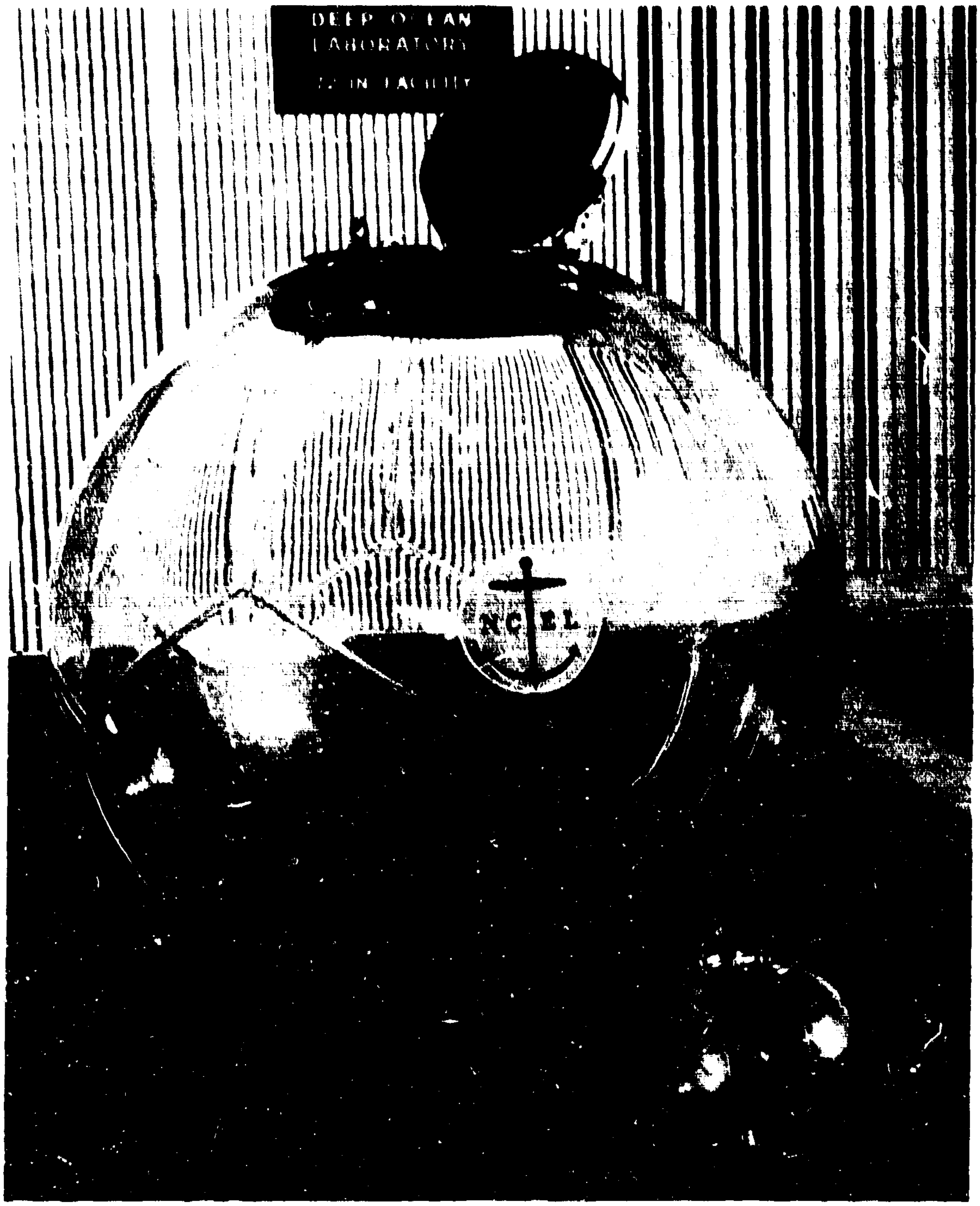


Figure 1. NEMO Model 600 capsule with hull #3; 15-inch NEMO model is shown for scale.

Table 1. NEMO Model 600 Capsule #3 Fabrication Data

MATERIALS*

Metal Closures[1]

Material	Annealed 4130 steel
Tensile Yield Strength, psi	45,850 (average)
Tensile Ultimate Strength, psi	81,800 (average)
Elongation (2-inch gage length), percent	29 (average)

Acrylic Hull[2]

Material	Plexiglas G			
Tensile Ultimate Strength, psi	10,700	max.	10,000	min.
Elongation at Rupture, percent	6.0	max.	3.5	min.
Tensile Modulus, psi	5.1×10^6	max.	4.2×10^6	min.
Shear Strength, psi	11,200	max.	9,400	min.
Flexural Strength, psi	17,100	max.	14,000	min.
Flexural Modulus, psi	4.8×10^6	max.	4.5×10^6	min.
Compressive Yield Strength, psi	17,100	max.	16,500	min.
Compressive Modulus, psi	4.9×10^6	max.	4.5×10^6	min.
Deformation Under Comp. Load, percent (4000 psi at 122°F for 24 hours)	1.2	max.	0.7	min.

DIMENSIONS

Thickness, inches (70 measurements)	2.607	max.	2.498	min.
Radius, inches (70 measurements)	33.100	max.	32.956	min.
Diameter, inches (16 measurements)	66.090	max.	66.035	min.

JOINTS[3]

Tensile Ultimate Strength, psi (Tests performed by NCEL)	8640	max.	6860	min.
Tensile Ultimate Strength, psi (Tests performed by Swedlow Inc)	9150	max.	8000	min.

*Number of test specimens taken are: (1) 2, (2) 120, (3) 16

Table 2. Specified* Properties of Acrylic Plastic

Physical Properties

Property	Typical	Test Method
Hardness, Rockwell M	90	ASTM-D785-62
Hardness, Barcol	90	ASTM-D2583
Specific gravity	1.19 ± 0.01 (2 tests within 0.005)	ASTM-D792-64T
Refractive index; 1/8 inch	1.50 ± 0.01	ASTM-D542-50
Luminous transmittance; 1/8 inch	91%	ASTM-D1003-61
Haze, 1/8 inch	2.3	ASTM-D1003-61
Heat distortion temperature		ASTM-D648-56
+3.6°F/min at 264 psi	200°F	
+3.6°F/min at 66 psi	220°F	
Thermal expansion/°F at 20°F	35×10^{-6}	Fed. Stan. 406 Method 2031
Water absorption; 1/8 inch		ASTM-D570-63T
(a) 25 hours at 73°F	0.3%	
(b) to saturation	1.9%	

Mechanical Properties

Property	Typical	Test Method
Tensile strength, rupture (0.2 in./min)	9,000 psi (min)	ASTM-D638-64T
Tensile elongation, rupture	2% (min)-7% (max)	ASTM-D638-64T
Modulus of elasticity, tension	400,000 psi (min)	ASTM-D638-64T
Compressive strength, (0.2 in./min)	15,000 psi (min)	ASTM-D695-63T
Flexural strength, rupture	14,000 psi (min)	ASTM-D790-63
Shear Strength, rupture	8,000 psi (min)	ASTM-D732-46
Impact strength, 1 zod (per inch of notch)	0.4 ft-lb (min)	ASTM-D256-56
Compressive deformation under load (4,000 psi at 122°F for 24 hours)	2% (max)	ASTM-D621-64

* Specification developed by NCEL for procurement of acrylic plastic plates to be utilized in the fabrication of man-rated pressure resistant windows and pressure hulls.

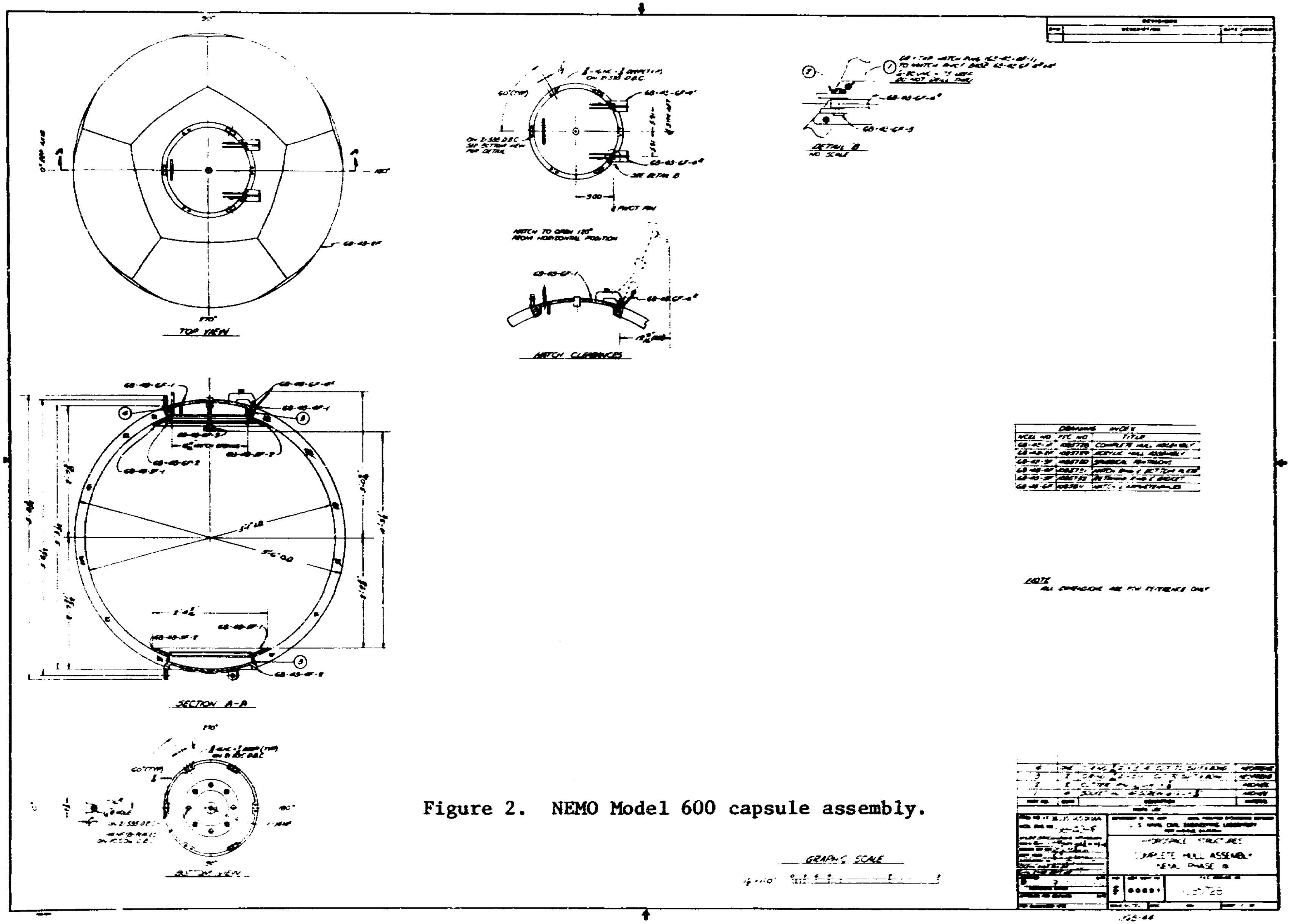


Figure 2. NEMO Model 600 capsule assembly.

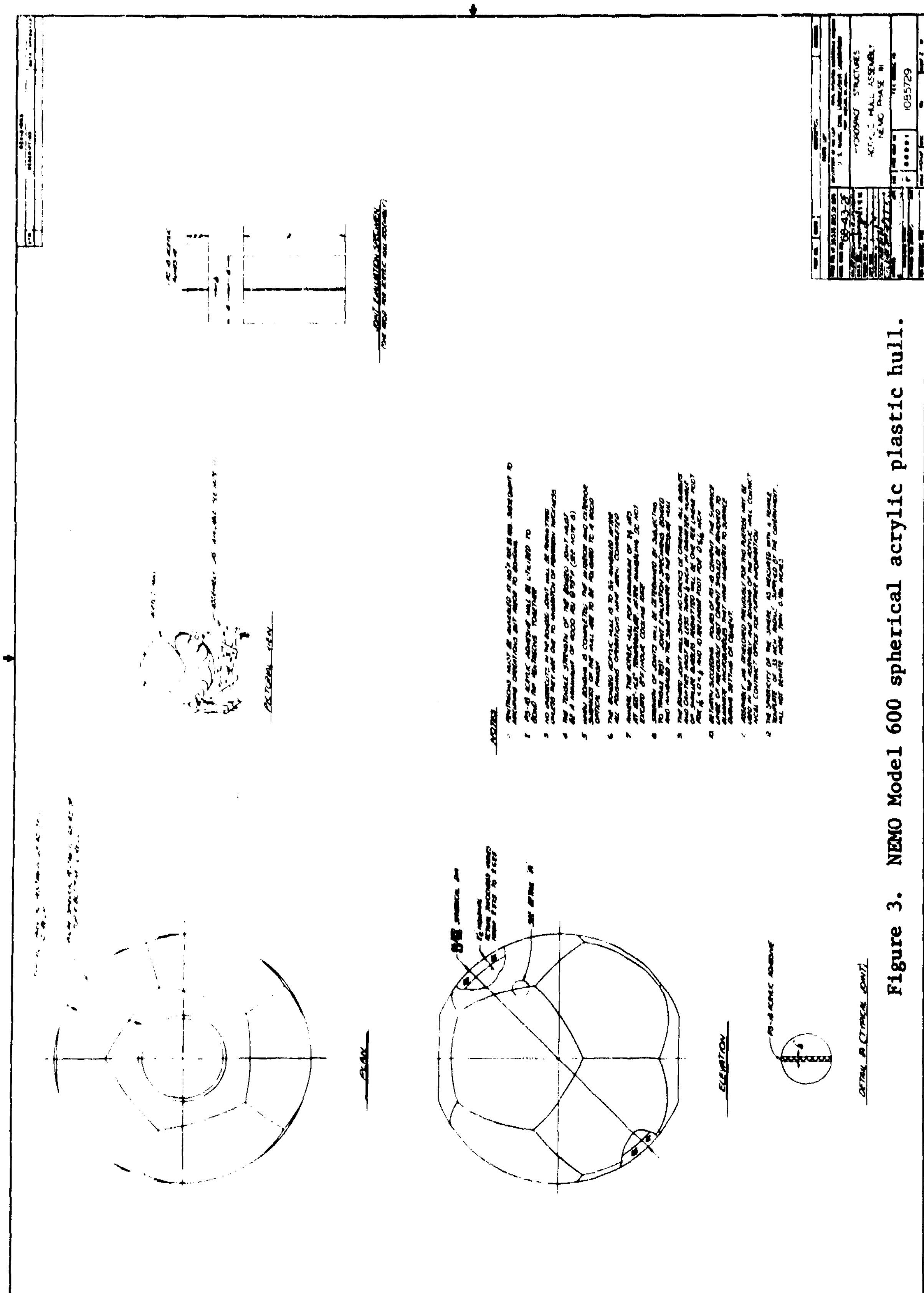


Figure 3. NEMO Model 600 spherical acrylic plastic hull.

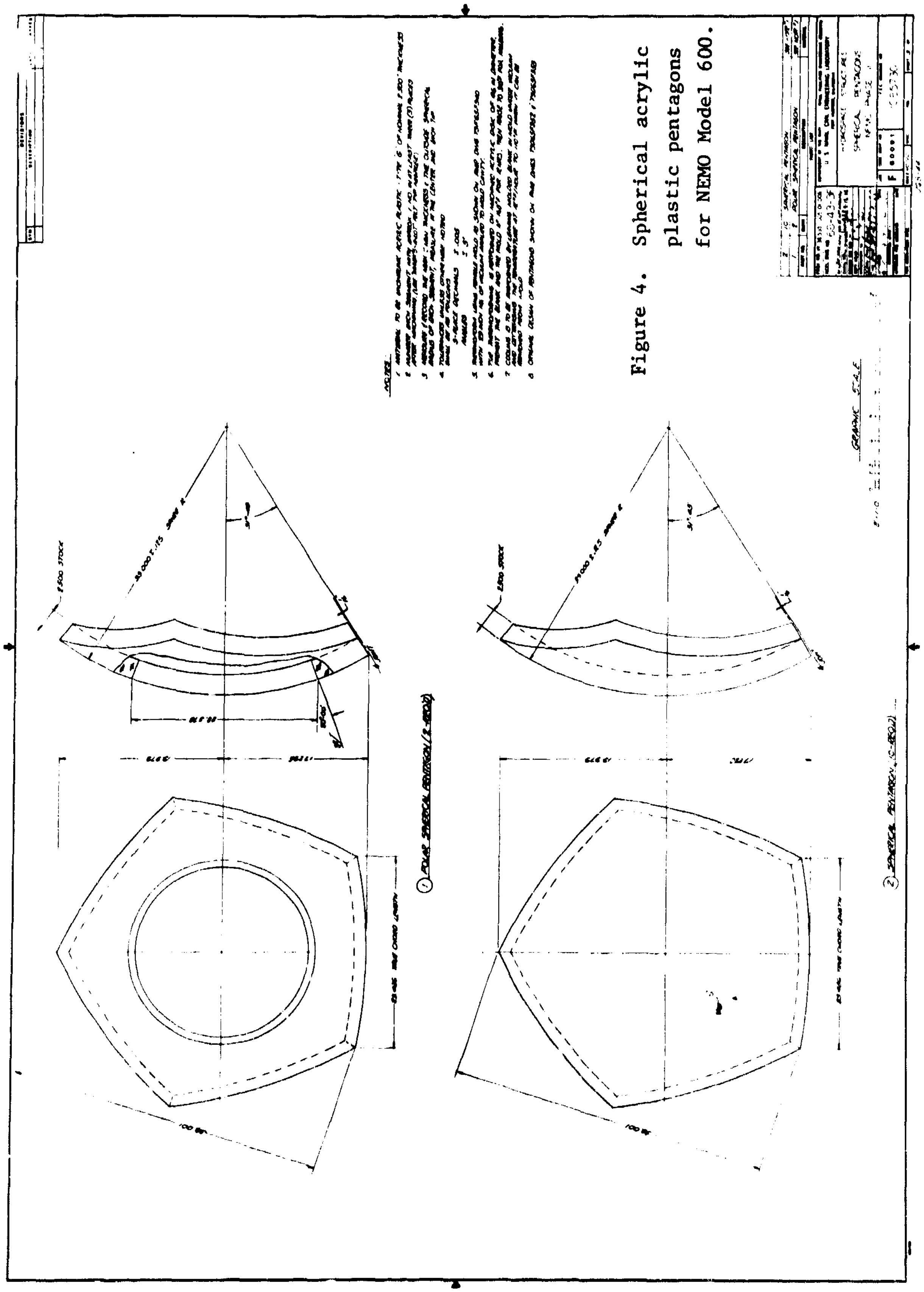


Figure 4. Spherical acrylic plastic pentagons for NEMO Model 600.

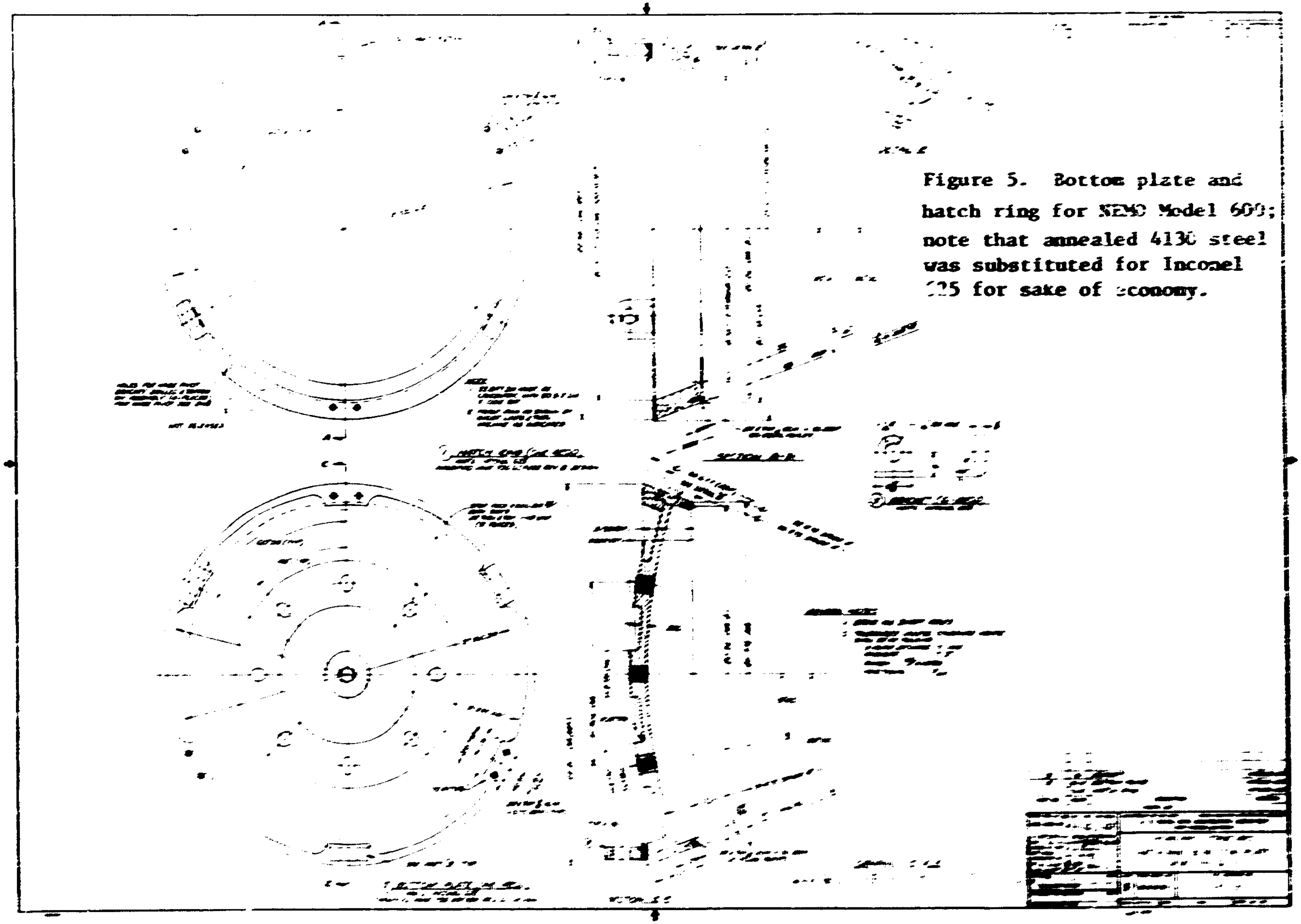


Figure 5. Bottom plate and hatch ring for NEMO Model 600; note that annealed 4130 steel was substituted for Inconel 625 for sake of economy.

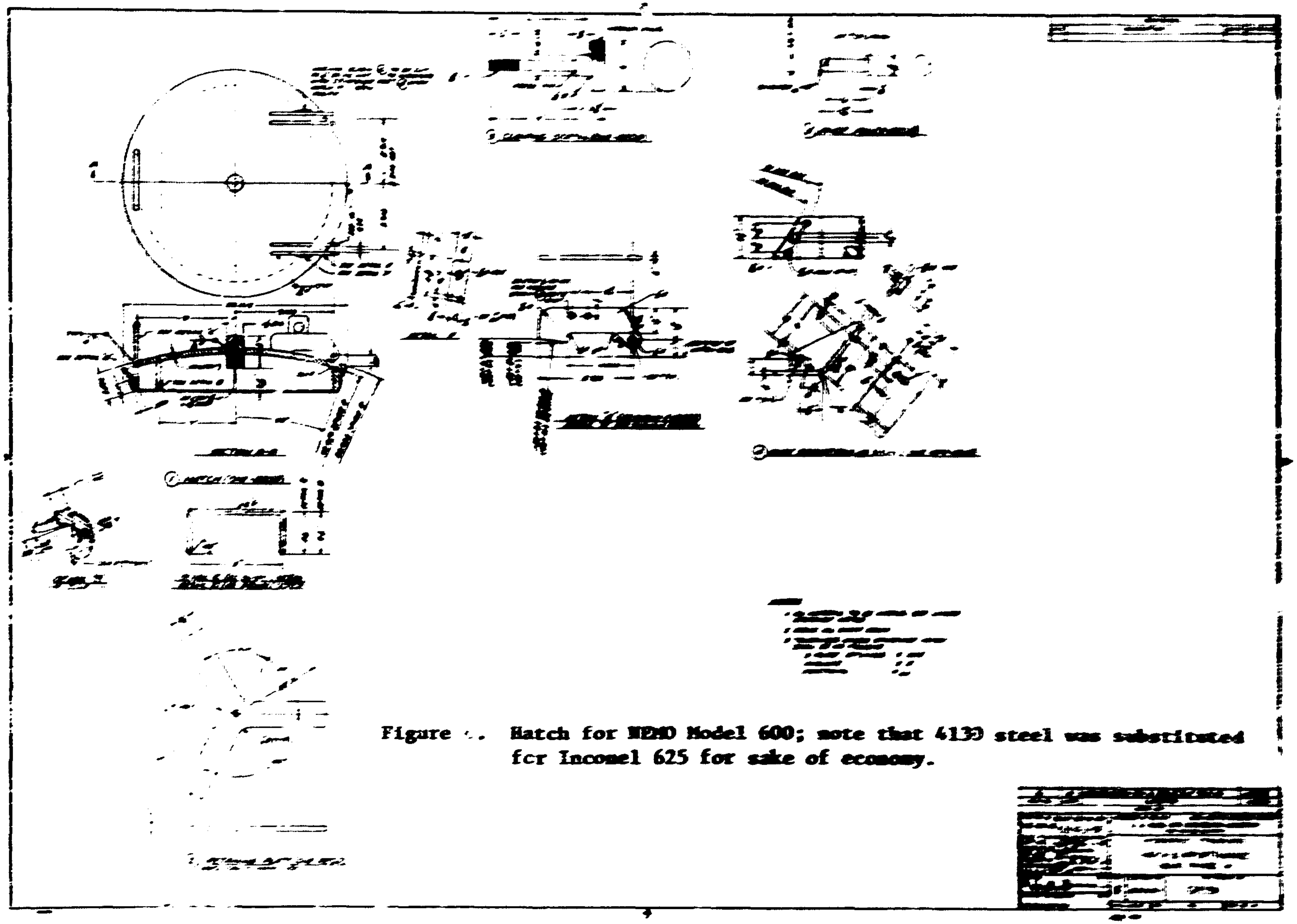


Figure .. Hatch for NEMO Model 600; note that 4130 steel was substituted for Inconel 625 for sake of economy.

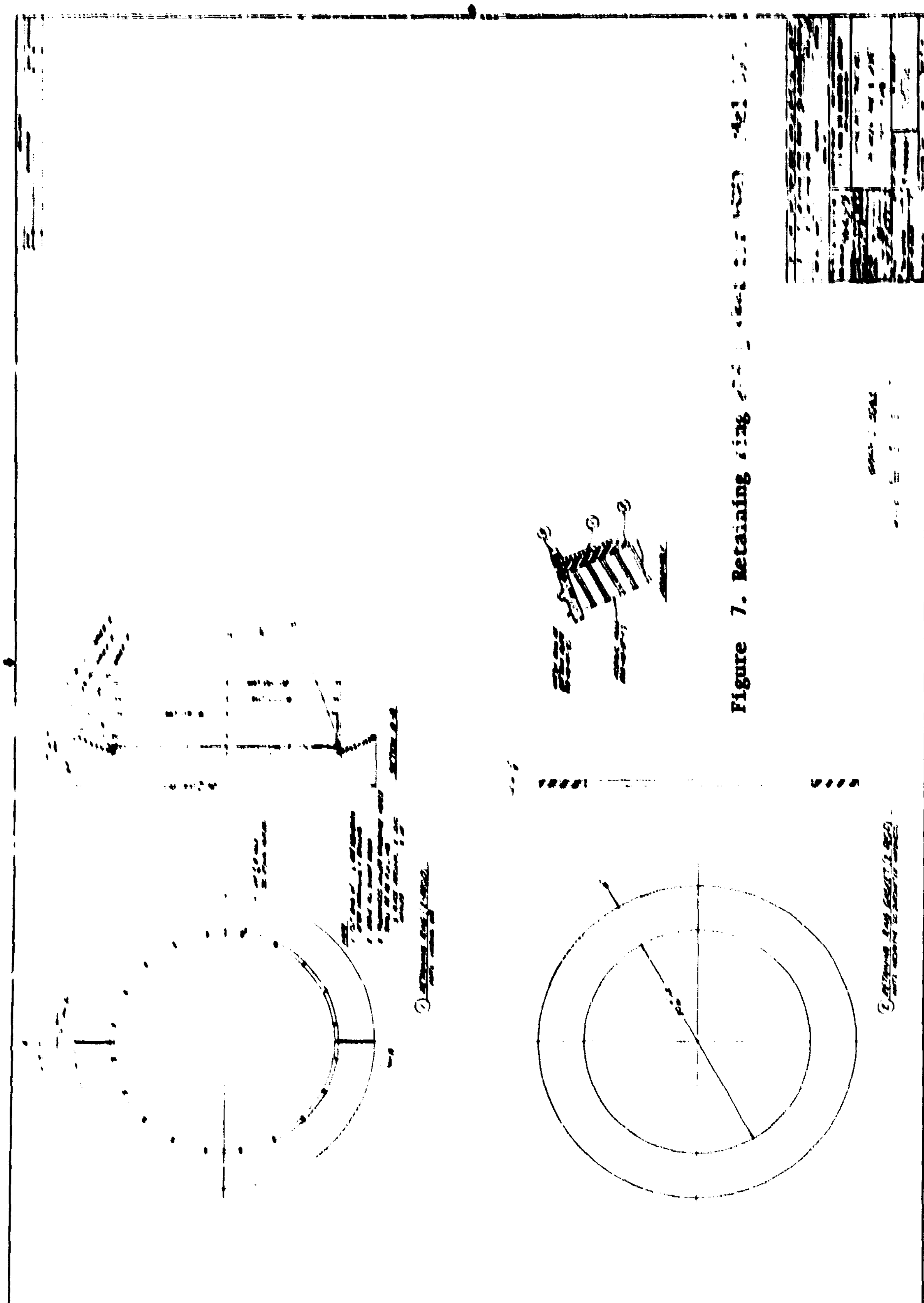


Figure 7. Retaining [illegible]

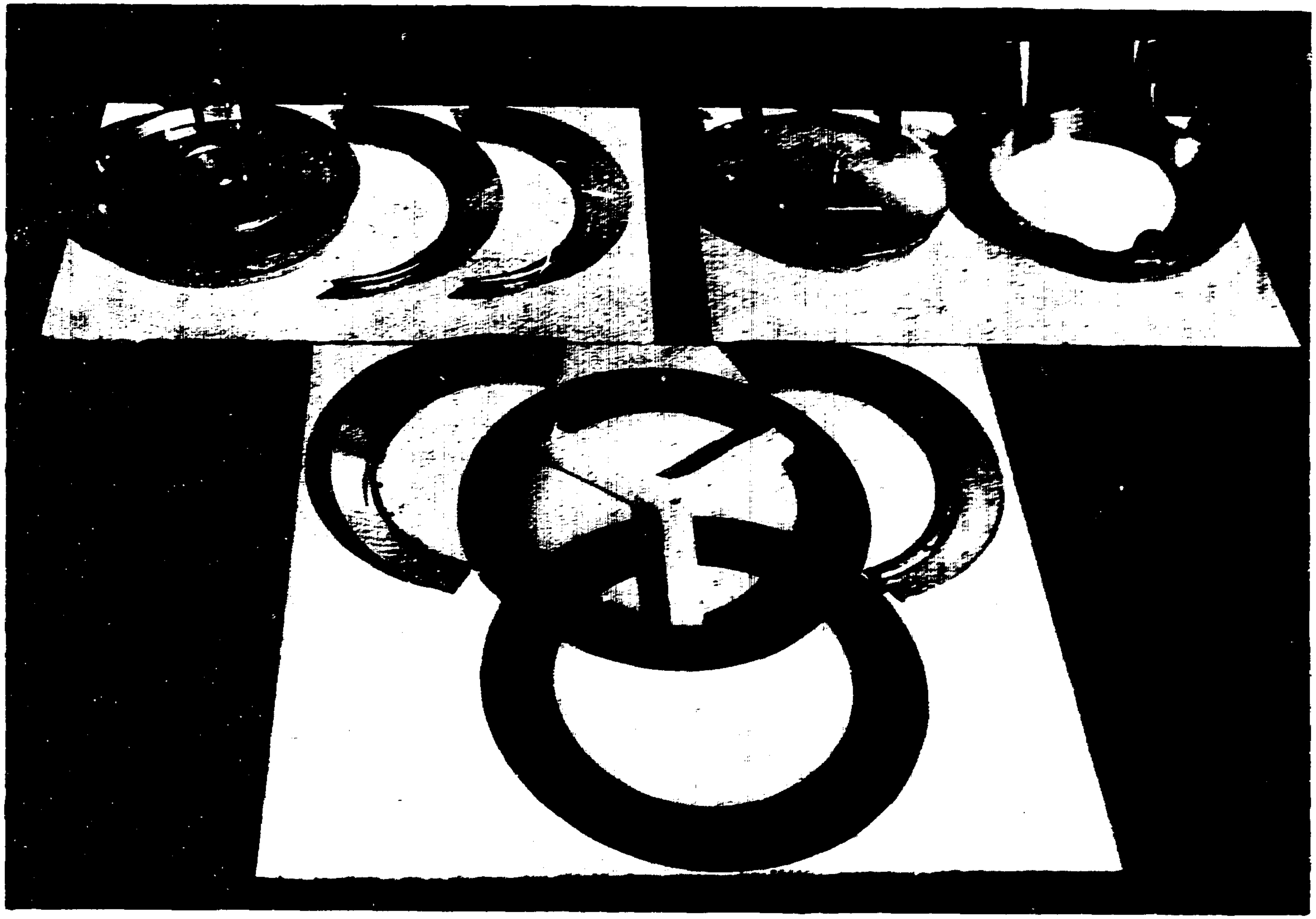


Figure 8. Components for the metallic polar closures in NEMO Model 600.

alloy closures gave them fair protection against the corrosive action of seawater. The 45,000 - 50,000 psi yield strength of annealed 4130 alloy was supposed to give the metal penetration closures approximately the same yield strength as that of medium cold worked 316 stainless steel forging.

TEST ARRANGEMENT

The same test arrangement was used for hull #3 as was previously used for hydrostatic testing of hull #0 (Figure 9). The assembled hull was placed inside a cage-like test jig and was fastened to it by bolting the bottom penetration plate to the support pedestal integral with the cage. Since hull #3 was not filled with water for the tests, the bottom plate had to resist 4000 lb upward pull when the cage assembly was placed in the water-filled 72-inch diameter pressure vessel.

TEST PROCEDURE

The hydrostatic pressure cycling procedure consisted of pressurizing the pressure vessel interior with 70°F tap water at 100 psi/minute rate till the desired pressure level was reached. Once the desired pressure level was reached, the valves were closed locking the pressurized water inside the vessel. After approximately 45 minutes, the valves were opened and the vessel was depressurized at 100 psi/minute rate. The vessel remained unpressurized for the same length of time that it was previously pressurized. The complete fatigue cycle consisting of pressurizing, sustained pressure loading, depressurizing, and relaxation required approximately 120 minutes.

The pressure cycling program consisted of four phases separated by removal and inspection of the hull for cracks in the acrylic and plastic deformation of the metallic penetration closures.

<u>Phase 1</u> - Pressure cycle hull #3 to 550 psi 815 times. During a typical sustained pressure loading, the pressure dropped from 550 to 528 giving an average 539 psi pressure level equivalent to 1200-foot depth (Figure 10).

<u>Phase 2</u> - Pressure cycle hull #3 to 700 psi 178 times. During a typical sustained pressure loading the pressure dropped from 700 to 675 psi giving an average 687 psi pressure level equivalent to 1540-foot depth (Figure 11).

<u>Phase 3</u> - Pressure cycle hull #3 to 950 psi 117 times. During a typical sustained pressure loading the pressure dropped from 950 psi to 910 giving an average 930 pressure level equivalent to 2080-foot depth (Figure 12).

<u>Phase 4</u> - Pressure cycle hull #3 to 950 psi 140 times. During a typical sustained pressure loading the pressure dropped from 950 psi to 830 psi giving an average 890 psi pressure level equivalent to 2000-foot depth.

The magnitude of pressure drop during sustained loading was the sum of (1) hull shrinkage under load, (2) changes in temperature, and

Figure 9. Jig for hydrostatic testing of NEMO Model 600 in NCEL's 72-inch diameter Deep Ocean Simulator.

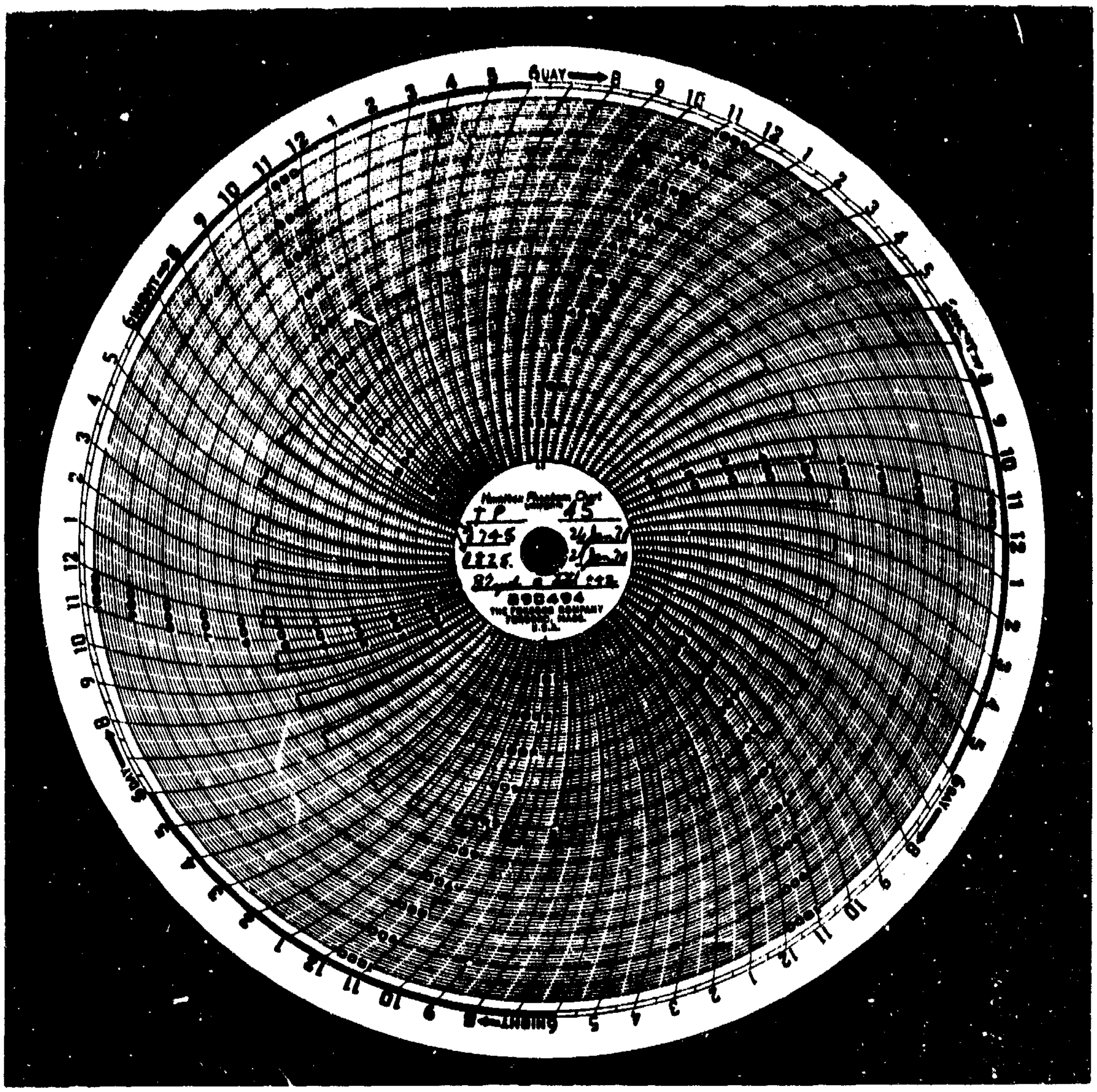


Figure 10. Typical pressure versus time record of cyclic tests to 1200 foot depth.

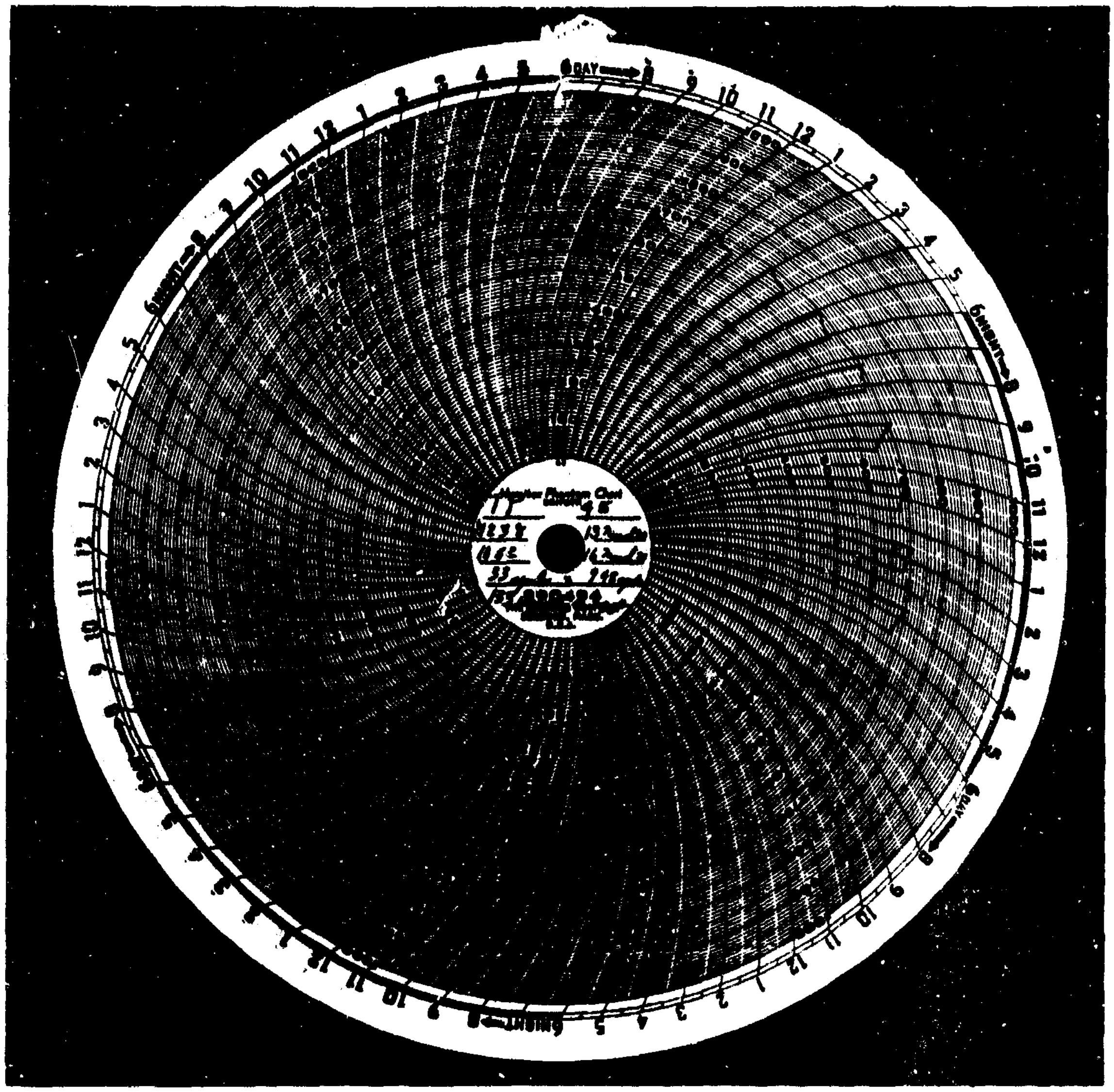


Figure 11. Typical pressure versus time record of cyclic tests to 1540 foot depth.

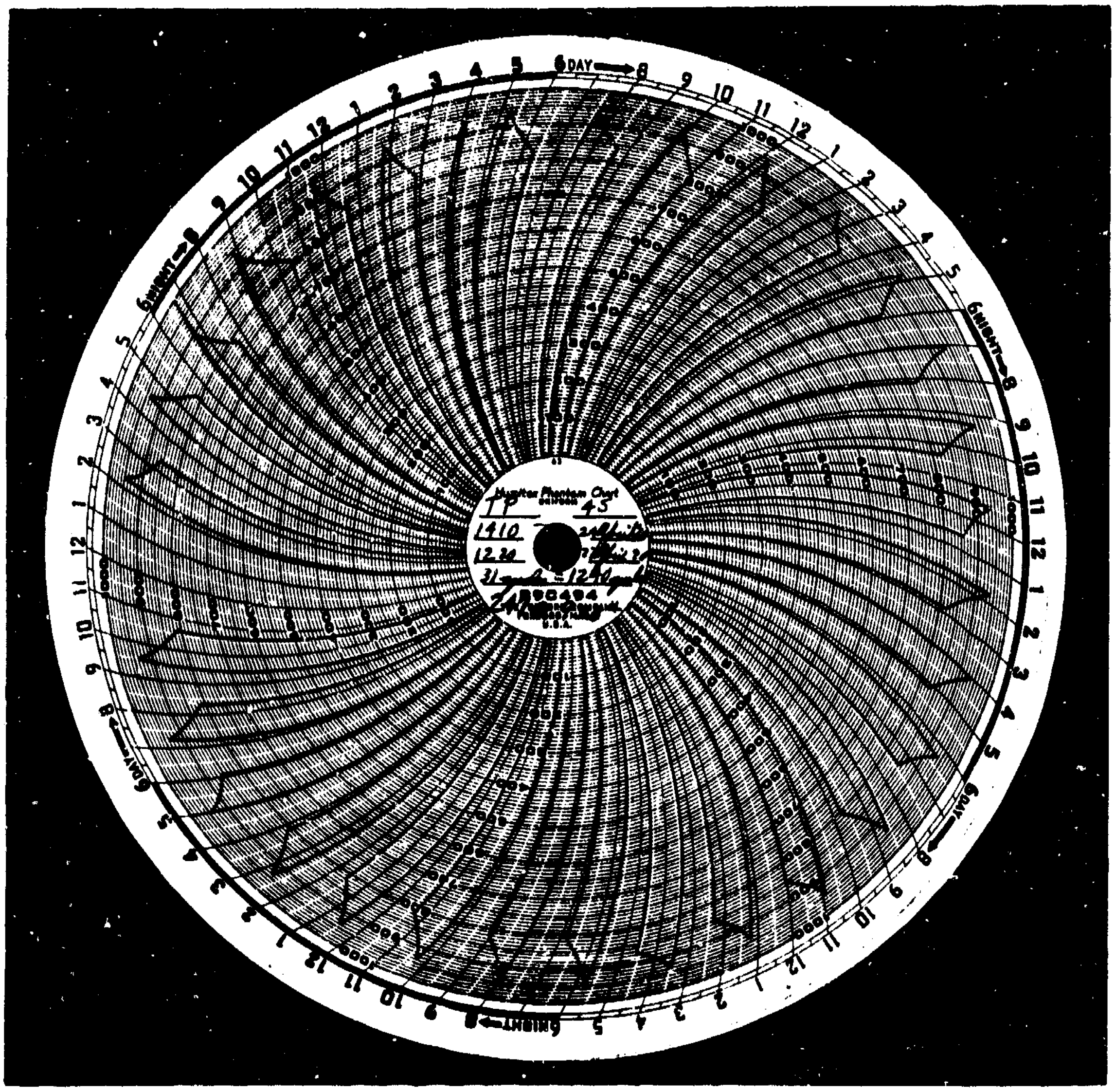


Figure 12. Typical pressure versus time record of cyclic tests to 2000 foot depth.

(3) leakage past the solenoid operated shut-off valve. Since the pressure cycling control mechanism operated unattended malfunctions often occurred. These malfunctions generally resulted in pressure cycles of unequal length, some sustained loadings being only 15 minutes long while others were 100 minutes long. Such malfunctions occurred seldom, influencing only about 1 percent of the pressure cycles.

There was one malfunction of the cycling control mechanism that was more serious than the others as it caused the pressurization to continue to approximately 1000 psi. This malfunction occurred in Phase 4 of the program at the 101st pressure cycle.

TEST OBSERVATIONS

Since hull #3 was visually inspected five times during the cyclic fatigue evaluation program, the results of the observations are stated accordingly.

Inspection of Hull #3 Prior to Cycling

Detailed inspection of the hull failed to detect any separation cracks or crazings in the acrylic plastic or components of the metallic penetration closures. The adhesive bonded joints contained a small number of air bubbles whose location was carefully noted.

Inspection of Hull #3 After Phase 1 of Cyclic Tests

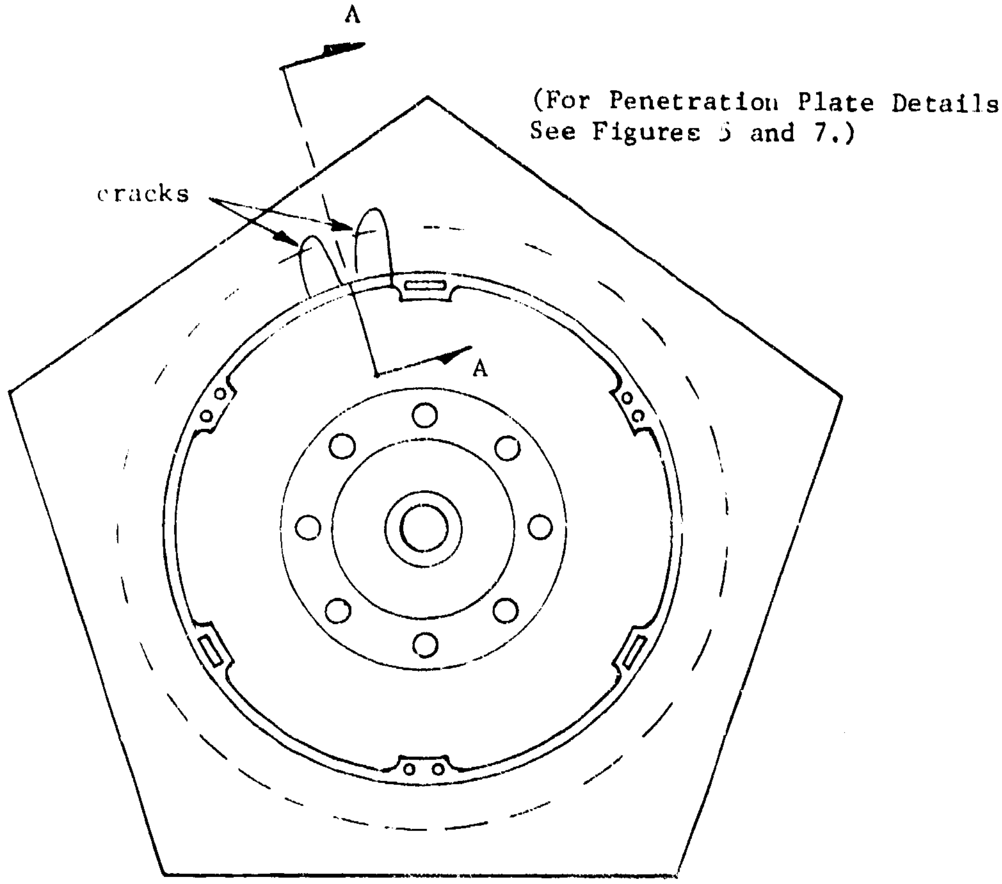
No cracks or crazing was found anywhere in or on the acrylic plastic hull, or components of the metallic end-closures. The air bubbles inside the adhesive bonded joints did not enlarge or serve as crack initiators.

Inspection of Hull #3 After Phase 2 of Cyclic Tests

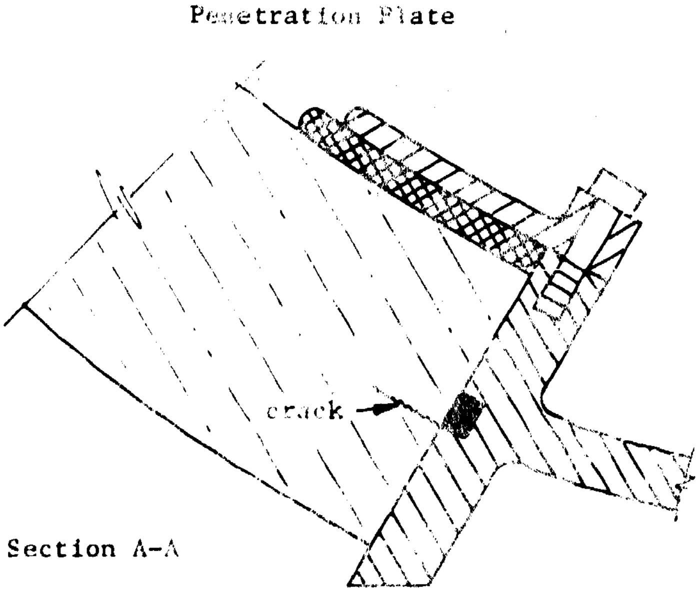
No cracks were found inside the adhesive filled joints of the acrylic plastic hull, or components of the metallic end-closures. The air bubbles inside the adhesive bonded joints did not enlarge or serve as crack initiators. Slight surface crazing was observed on all the acrylic plastic bearing surfaces in contact with the metallic penetration closures. Two small cracks of 0.250 penetration and 0.250 length were found in the plastic bearing surface in contact with the bottom steel penetration closure (Figure 13).

Inspection of Hull #3 After Phase 3 of Cyclic Tests

Several cracks of 0.250-inch penetration, 0.500-inch length, and less than 0.001-inch width were found in the acrylic plastic bearing surface in contact with the bottom steel penetration closure. The cracks were located around the circumference of the polar opening in the midplane of the hull wall. In all cases, these cracks originated at the bearing



Bottom View of Polar
Opening for the Bottom
Penetration Plate



Section A-A

Figure 13. Appearance of first cracks at the conclusion of Phase 2 cyclic tests.

surface and their penetrations were oriented at right angle to it. As the cracks penetrated further they tended to follow the curvature of the hull. The cracks were located in the same place and were of the same shape as those in the 15-inch NEMO models tested in the previous study. No cracks or crazing was observed in the adhesive filled joints and the voids there did not enlarge or serve as crack initiators.

Inspection of Hull After Phase 4 of Cyclic Tests

The previously observed cracks on the acrylic plastic bearing surface in contact with bottom steel closure penetrated the hull further, reaching approximately 0.500 inches in penetration. Only a few more cracks also 0.500 inches in penetration were noted on the same bearing surface.

A multitude of new cracks were noted on the top acrylic plastic bearing surface in contact with the hatch ring. Those cracks were of approximately 2.0-inch penetration and several inches long. They were located at midplane and in the inner half of hull thickness (Figures 14, 15, and 16).

Several separation voids were found inside the adhesive filled joints. They did not originate at existing air bubbles inside the adhesive. These separation voids were less than 0.5-inch in diameter, about 0.001 inches thick, and oriented parallel to the edges of the acrylic pentagons. In all cases, they were located at midplane of the hull thickness in contact with the pentagon edge (Figure 17). The separation voids were characterized by their knife edge thickness and scallop marks on the top and bottom surfaces of the separation voids.

The top hatch exhibited typical plastic buckling of sufficient magnitude to result in complete reversal of hatch curvature (Figure 18). Where previously the hatch was convex, now it is concave. No cracks were observed in the plastically buckled hatch and the cadmium plating did not spall off from the yielded steel.

Neither the hatch ring nor the bottom penetration plate showed any signs of plastic deformation.

FINDINGS

1. Plastic buckling of metallic hull components occurs first in the top hatch assembly in the 2080 to 2250-foot depth range.

2. The first cracks in the acrylic plastic were observed in the plastic bearing surface in contact with the bottom penetration after the hull has been consecutively subjected to approximately 993 pressure cycles of 45 minutes each sustained loading duration. Of these cycles 815 were to 1200-foot depth followed by 178 cycles to 1540-foot depth.

3. Cracks appeared in the plastic bearing surface in contact with the top hatch ring after a total of 1250 cycles. Of these 815 cycles were

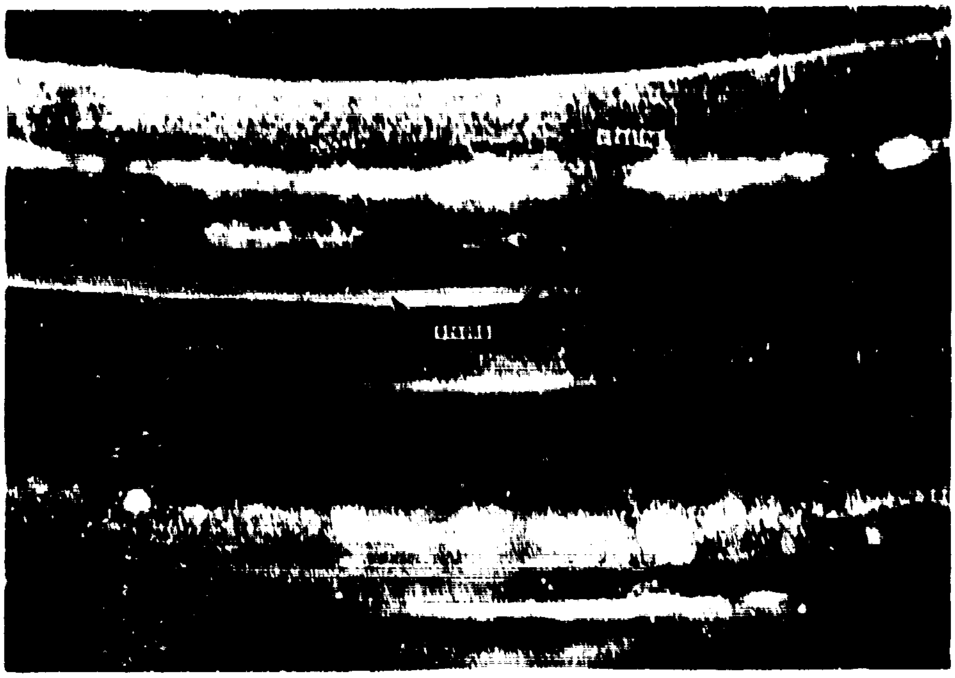


Figure 14. Typical crack in the acrylic plastic bearing surface in contact with the hatch ring at the conclusion of Phase 4 cyclic tests; view normal to the bearing surface.

Figure 15. Typical cracks in the acrylic plastic bearing surface in contact with the hatch ring at the conclusion of Phase 4 cyclic tests; view parallel to the bearing surface.

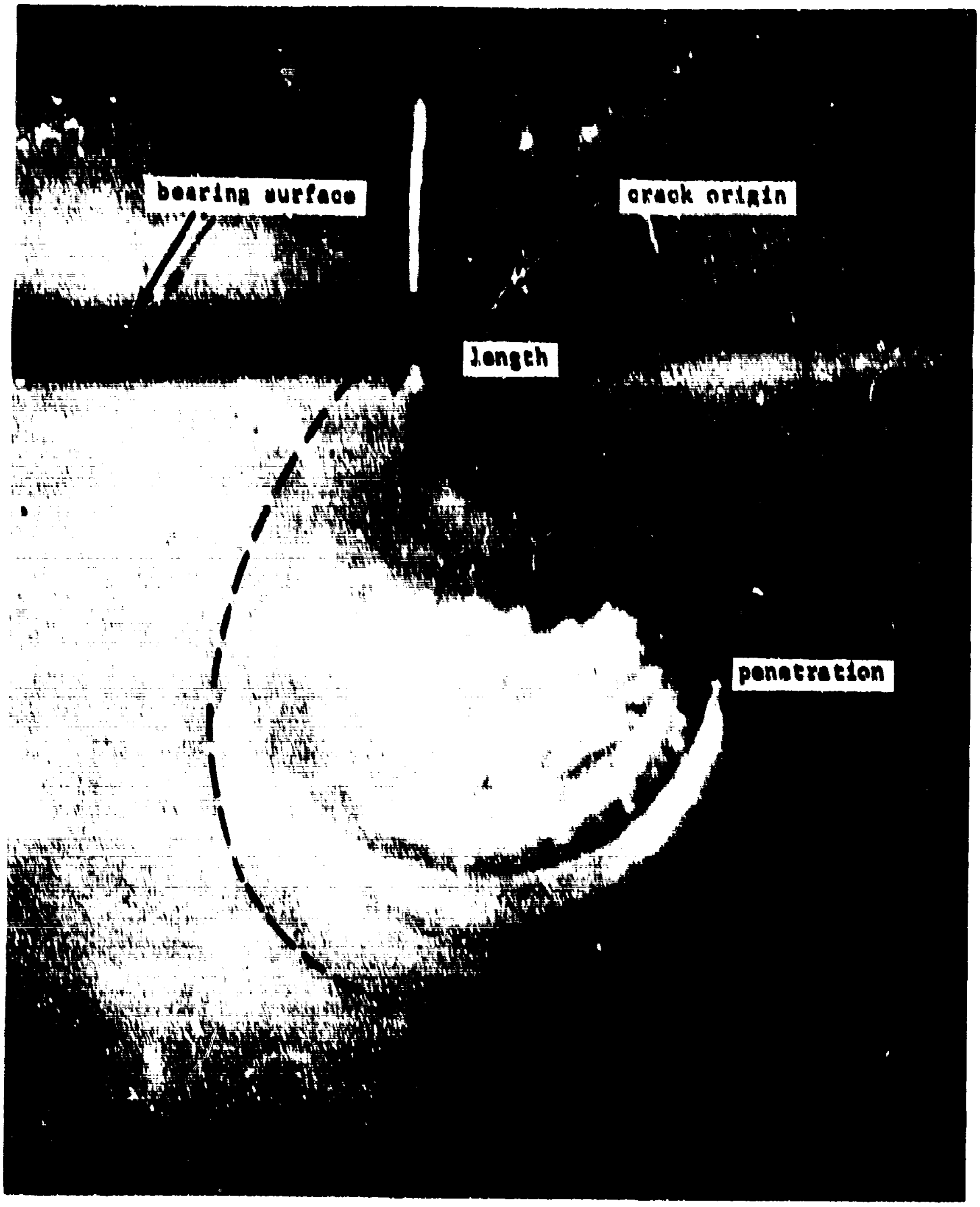
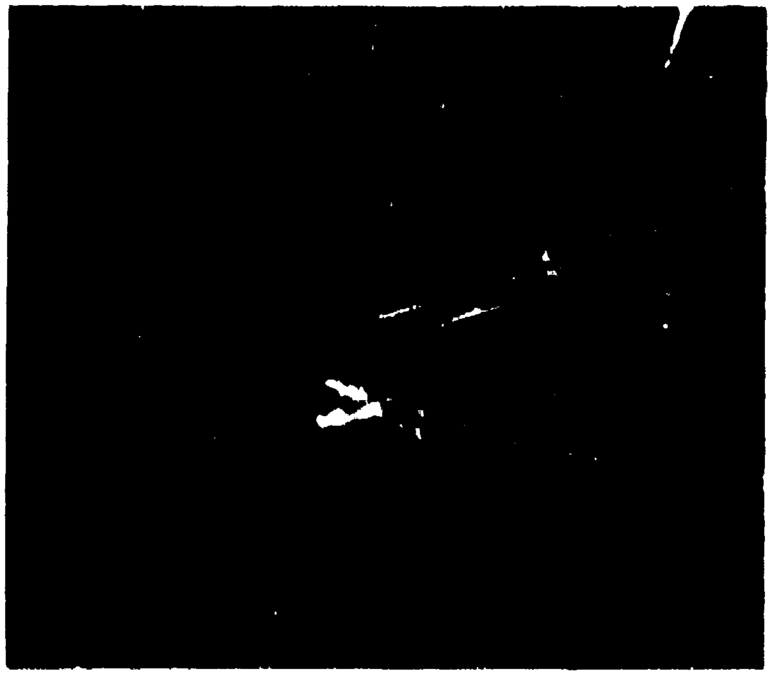


Figure 16. Detail of a typical crack shown in Figures 14 and 15.



Note the scalloped appearance of the surface (approx. 0.25-inch diameter).

Note the scalloped appearance of the surface (approx. 0.5-inch wide x 1.0-long).

Acrylic joint spacer (0.5 x 0.5 x 0.125 inches).

Figure 17. Separation voids in the joint at the conclusion of Phase 4 cyclic tests.

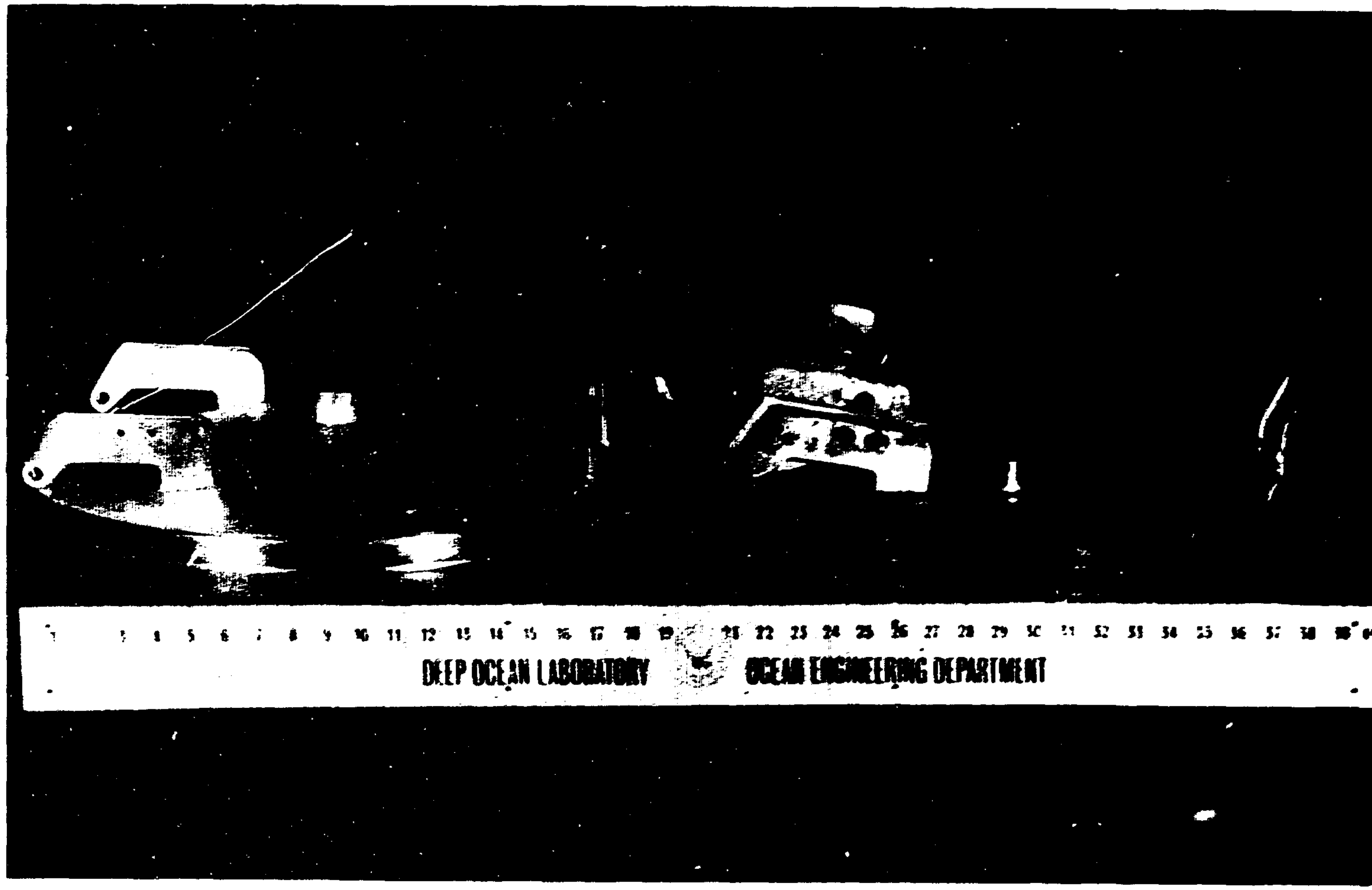


Figure 18. Comparison between the plastically buckled and a brand new hatch of annealed 4130 steel for NEMO Model 600 capsule.

to 1200-foot depth, 178 cycles to 1540-foot depth, and 257 cycles to 2080-foot depth.

4. Cracks were observed in the adhesive bonded joints at a few locations only after the hull was subjected to a total of 1250 cycles. Of these, 815 cycles were to 1200-foot depth, 178 cycles to 1540-foot depth, and 257 cycles to 2080-foot depth.

5. The location and character of the fatigue cracks were the same as in the 15-inch models tested previously indicating that cyclic fatigue data generated by testing of models is applicable to the 66-inch diameter NEMO capsules.

CONCLUSION

The hatch in the NEMO Model 600 possesses a safety factor of 3.8 based on the relationship between the 2250-foot depth where plastic buckling of 4130 annealed steel hatch occurs after repeated dives, and the 600-foot maximum operational depth.

The acrylic plastic hull of NEMO Model 600 possesses a safety factor of 7 based on the relationship between the 4150-foot implosion depth[1] under short-term loading and the 600-foot maximum operational depth.

The NEMO Model 600 can repeatedly withstand 1 hour long proof test dives to 1200-foot depth without generating fatigue cracks in acrylic plastic providing that the number of such proof test dives does not exceed 100.

RECOMMENDATIONS

When future NEMO Model 600 pressure hulls with 4130 steel end-closures are built, the minimum yield strength of the 4130 steel alloy could be increased, if so desired, to 130,000 psi by heat treatment to eliminate plastic buckling of the hatch prior to general implosion of the acrylic hull at 1850 psi.

REFERENCES

1. Technical Report R-676, "Development of a Spherical Acrylic Plastic Pressure Hull for Hydrospace Application," by J. D. Stachiw, U. S. Naval Civil Engineering Laboratory, April 1970.

2. Technical Note N-1113, "The Spherical Acrylic Pressure Hull for Hydrospace Application; Part II - Experimental Stress Evaluation of Prototype NEMO Capsule," by J. D. Stachiw and K. L. Mack, U. S. Naval Civil Engineering Laboratory, April 1970.

3. Technical Note N-1094, "The Spherical Acrylic Pressure Hull for Hydrospace Application; Part III - Comparison of Experimental and Analytical Stress Evaluations," by H. Ottsen, U. S. Naval Civil Engineering Laboratory, March 1970.

Appendix A

FABRICATION REPORT - NEMO ACRYLIC SPHERE NO. 3

1. Twelve acrylic sheets, 48 inches by 60 inches by 2-1/2 inches thick were rough sawed to a 46-inch diameter. The periphery was machined to a 200 micro-inch finish. One edge was then chamfered to 1/16-inch by 1/16-inch.

   Each machined blank was serialized and the thickness measured. The results of the thickness measurement are contained in Attachment I (Figure A-1).

2. One blank at a time was set in a female form die, Drawing Number TSF65F325, with the chamfered edge against the die.

3. The flat acrylic blank and form die were placed in an oven. A vacuum line was run from a vacuum pump outside the oven, to the center of the form die where the vacuum holes are located.

   The oven was preheated to +165°F over night.

4. After preheating, forming was accomplished as follows:

   a) The oven temperature was raised to +310°F

   b) After eight hours at +310°F, vacuum was applied and the blank formed to contour

   c) After fifteen minutes under vacuum, the oven was turned off. Vacuum was left on and the oven doors remained closed.

   d) The oven was allowed to cool overnight, a minimum of sixteen hours. The oven doors were opened and the formed part in the form die was allowed to cool to room temperature.

5. The above procedure was followed for all twelve acrylic blanks.

6. Each of the formed spherical blanks were checked for contour and thickness. The results of the thickness measurement are contained in Attachment 1.

7. Each of the formed spherical blanks were annealed for twenty-four hours at +160°F. The blanks were cooled at a rate not exceeding eight degrees per hour, to room temperature. Each spherical blank was annealed in the form die.

8. Each of the formed spherical blanks were machined into a pentagon section, on a milling machine, in accordance with Drawing Number 1085730.

9. A hole was machined in two of the spherical pentagon sections with a vertical boring mill. This was done in accordance with Drawing Number 1085730. These two sections are used at the polar regions of the sphere.

10. Each of the machined spherical pentagons were annealed for twenty-four hours at +160°F. The pentagons were cooled at a rate not exceeding eight degrees per hour, to room temperature. Each spherical pentagon was annealed in the form die.

    The machined spherical pentagons were reinspected for contour. The results are contained in Attachment I.

11. The periphery of each pentagon was sanded using 240 to 400 grit sandpaper.

12. One polar zone pentagon and five regular spherical pentagons were positioned in the handling fixture, Drawing Number SK67154, hemispherically with the polar zone pentagon at the bottom center and the other five encompassing it. The pentagons were spaced 0.125 inches apart with acrylic spacers (0.250 inch by 0.500 inch). These spacers were located two on a pentagon side and approximately two inches in from each corner. The joints between the segments were matched on the outside surface so the external curvature across the joint was continuous.

13. The 0.125 inch spaces between the pentagon segments were prepared for cementing as follows:

    a) The joint on each side was covered with an adhesive backed aluminum foil (Scotch Brand No. 425). The adhesive backed aluminum foil was formed in a manner to allow it to protuberate slightly over the joint area. This protuberance left a bead in the cementing operation which compensated for shrinkage in the cemented joint.

14. Swedlow's proprietary casting material, identified as SS-6217, was utilized to bond the pentagons together. SS-6217 was evaluated before and after sea water exposure. The results were forwarded to and approved by NCEL.

15. A filling arrangement was adapted to the taped joints to allow cementing of the six pentagon sections in two operations.

16. The hemisphere was poured and the adhesive cured. (Details of the adhesive and cure are proprietary to Swedlow Inc.)

17. The first hemisphere was removed from the fixture with a hoist and sling. The second hemisphere was constructed in the same manner in accordance with paragraphs 11 through 16 using 0.188 inch acrylic spacers and was left positioned in the fixture.

18. The first hemisphere was elevated above the second one with a hoist and sling. It was positioned in place on the second hemisphere with the 0.125 inch acrylic spacers as described in paragraph 12. The joints were prepared and the adhesive poured as described in paragraphs 13 through 16. The joining of the two hemispheres completed the acrylic sphere.

19. When the adhesive backed aluminum foil was removed from the sphere, a number of bubbles were evident in the cement joint.

20. To repair the joint required that the bubbled area be removed by machining or drilling.

    After the bubbled area was removed the sphere was annealed at $160^{\circ}F$ for a period of twenty-seven hours. The sphere was cooled at a rate not exceeding eight degrees per hour until it reached room temperature. It was then removed from the oven.

21. The areas to be repaired were then filled with Swedlow's adhesive identified as SS-6217 and then cured.

22. This procedure, paragraphs 20 and 21, was followed until the majority of the bubbles were repaired.

23. After repair, the adhesive beads were removed and cleaned.

24. The completed sphere was then polished to remove scratches.

25. The completed sphere was then annealed, in the fixture, for a period of twenty-seven hours at $160^{\circ}F$. The sphere was cooled at a rate not exceeding eight degrees per hour until it reached room temperature. It was then removed from the oven.

26. The annealed acrylic sphere was moved to a temperature controlled room where it was allowed to equalize to the temperature of the room. The sphere was then measured for conformance to FEC Drawing Number 1085729, "Hydrospace Structures - NEMO Phase III Acrylic Hull Assembly".

27. The completed and accepted acrylic sphere was protected with Protex 20V protective paper, packaged and delivered to Naval Civil Engineering Laboratory.

28. Four test coupons, four inches wide by twelve inches long by 2.5 inches thick, were bonded together using the Swedlow adhesive SS-6217 and annealing procedures representative of the full acrylic hull. One test coupon was identified and delivered to the Naval Civil Engineering Laboratory for testing.

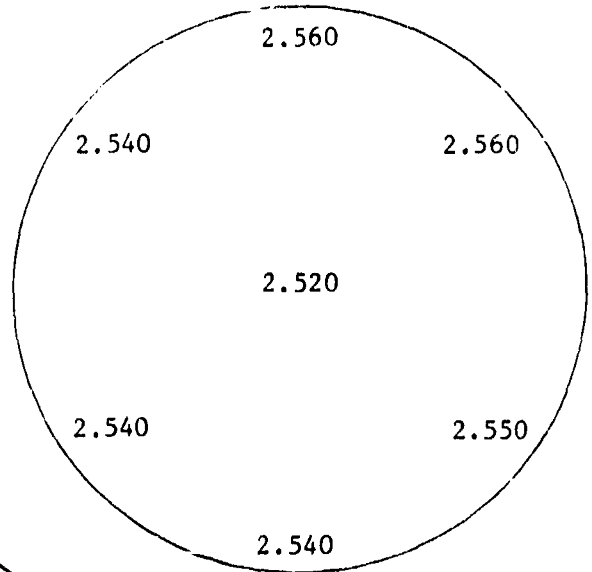
29. The second test coupon was tested by Swedlow. The results are contained in Attachment III.

Attachment #1 FINAL PENTAGON INSPECTION

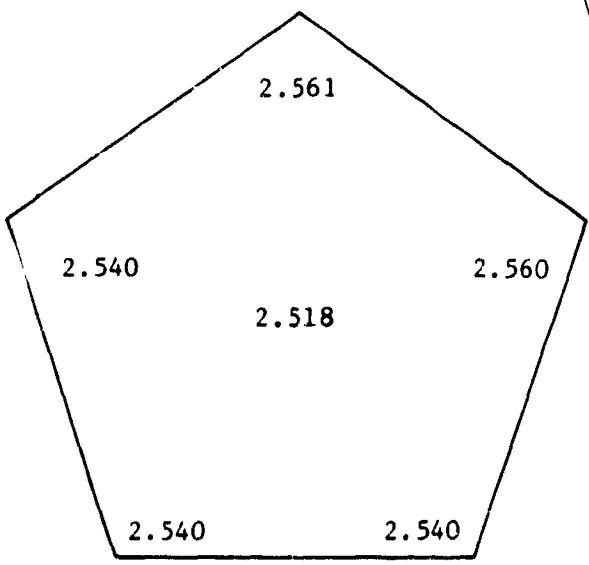
Pentagon No. #107

Inspector ____________

Date 30 September 1969

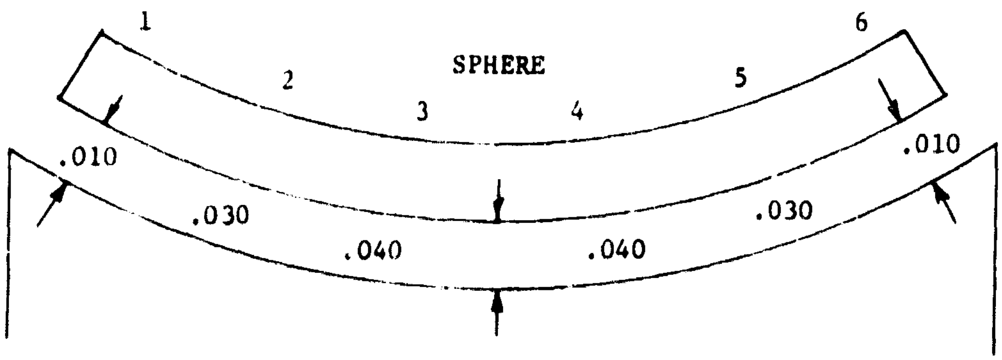


THICKNESS CHART BEFORE FORMING



THICKNESS CHART AFTER FORMING

SHORT CORD MEASUREMENT	LONG CORD MEASUREMENT
1. 23.500	1. 38.003
2. 23.501	2. 37.999
3. 23.495	3. 37.996
4. 23.497	4. 37.996
5. 23.498	5. 37.999



CONTOUR TEMPLATE AFTER MACHINING

Figure A-1. Typical Dimensional Control Form for Individual Pentagons Used by Swedlow Inc. During Fabrication of NEMO Hull #3.

DELSEN corporation
TESTING LABORATORIES
719 W. BROADWAY • GLENDALE CALIFORNIA 91204

TEST REPORT

Sundize, Inc.
12605 Beach Blvd.
Garden Grove, Calif. 92642

6/18/69 T.5931 1 14 14800

SHEAR STRENGTH
Tested at Room Temperature after a Minimum of 40 Hours at 23°C & 50% R.H.
Rate of Test: 0.05"/Minute
Punch Diameter: 1.000"

SPECIFICATION: ASTM D 732-46

SPECIMEN	THICKNESS INCHES	MAXIMUM LOAD LBS.	SHEAR STRENGTH PSI
101			
-1	0.275	9,640	11,200
-2	0.273	10,240	11,900
102			
-1	0.271	10,500	12,300
-2	0.271	7,120	8,360
103			
-1	0.264	7,560	9,120
-2	0.267	7,960	9,440
104			
-1	0.275	8,160	9,450
-2	0.274	7,840	9,110
105			
-1	0.273	8,380	9,770
-2	0.276	8,860	10,200
106			
-1	0.263	7,720	9,340
-2	0.272	8,000	9,360
107			
-1	0.247	7,400	9,540
-2	0.248	7,320	9,400
108			
-1	0.247	7,480	9,640
-2	0.250	8,480	10,800

(continued)

DELSEN corporation
TESTING LABORATORIES
719 W. BROADWAY • GLENDALE CALIFORNIA 91204

T.5931 7 14

COMPRESSIVE STRENGTH & MODULUS
Rate of Test: 0.05"/Minute
Tested at Room Temperature after a Minimum of 88 Hours at 23°C and 50% Relative Humidity

SPECIFICATION: ASTM D-695-63T

SPECIMEN	WIDTH INCHES	DEPTH INCHES	LENGTH INCHES	YIELD LOAD LBS.	COMPRESSIVE YIELD STRENGTH PSI	COMPRESSIVE MODULUS PSI x 10^5
HULL #2 & #3						
101-1	0.501	0.504	1.500	4,160	16,500	4.8
-2	0.502	0.500	1.500	4,180	16,700	4.7
102-1	0.503	0.504	1.504	3,970	15,700	4.6
-2	0.508	0.505	1.502	4,380	16,900	4.8
103-1	0.503	0.504	1.502	4,370	16,800	4.8
-2	0.504	0.503	1.500	4,250	16,800	4.8
104-1	0.502	0.504	1.497	4,200	16,600	4.9
-2	0.502	0.501	1.501	4,190	16,700	4.8
105-1	0.502	0.501	1.502	4,260	16,900	5.0
-2	0.504	0.504	1.502	4,230	16,700	4.9
106-1	0.502	0.502	1.800	4,220	16,700	4.9
-2	0.502	0.506	1.499	4,270	16,800	4.8
107-1	0.500	0.505	1.493	4,240	16,800	4.9
-2	0.503	0.503	1.498	4,280	16,700	4.9
108-1	0.502	0.503	1.552	4,280	16,800	4.9
-2	0.503	0.505	1.552	4,260	16,800	4.9
109-1	0.503	0.500	1.507	4,160	16,500	4.8
-2	0.504	0.503	1.501	4,180	16,500	4.8
110-1	0.503	0.504	1.497	4,080	16,200	4.5
-2	0.502	0.503	1.503	4,270	16,900	4.6
111-1	0.503	0.505	1.506	4,350	17,100	4.9
-2	0.505	0.504	1.500	4,320	17,000	4.9

(cont.)

RESEARCH AND DEVELOPMENT MANUFACTURING TESTING

DELSEN corporation
TESTING LABORATORIES
719 W. BROADWAY • GLENDALE CALIFORNIA 91204

T.5931 14

TENSILE STRENGTH & MODULUS & ELONGATION
Rate: 0.05"/Min.
Tested at Room Temperature after a Minimum of 88 Hours at 23°C @ 50% R.H.

SPECIFICATION: ASTM D-638-64T

SPECIMEN	THICKNESS INCHES	WIDTH INCHES	MAXIMUM LOAD LBS.	TENSILE STRENGTH PSI	TENSILE MODULUS PSI x 10^5	ELONGATION %
HULL #2 & #3						
101-1	0.276	0.493	1,374	10,100	4.4	3.8
-2	0.275	0.493	1,438	10,600	4.4	6.3
102-1	0.275	0.494	1,438	10,600	4.4	4.9
-2	0.275	0.493	1,384	10,200	4.4	7.7
103-1	0.276	0.497	1,396	10,200	4.6	4.0
-2	0.275	0.495	1,456	10,700	4.5	5.2
104-1	0.275	0.495	1,462	10,700	4.7	4.9
-2	0.277	0.494	1,474	10,800	4.4	5.2
105-1	0.277	0.495	1,486	10,800	4.6	5.3
-2	0.275	0.493	1,458	10,800	4.6	4.8
106-1	0.275	0.492	1,364	10,100	4.5	3.6
-2	0.278	0.495	1,498	10,900	4.7	5.3
107-1	0.276	0.495	1,364	10,000	4.9	3.5
-2	0.276	0.494	1,410	10,300	4.7	3.9
108-1	0.255	0.498	1,340	10,600	4.7	4.1
-2	0.256	0.498	1,308	10,300	4.6	4.3
109-1	0.277	0.492	1,360	10,000	4.8	3.7
-2	0.276	0.492	1,452	10,700	5.1	5.0
110-1	0.275	0.495	1,442	10,600	4.6	5.1
-2	0.277	0.497	1,456	10,600	4.5	4.7
111-1	0.276	0.497	1,428	10,400	4.5	4.3
-2	0.275	0.505	1,466	10,600	4.2	4.8

(cont.)

DELSEN corporation
TESTING LABORATORIES
719 W. BROADWAY • GLENDALE CALIFORNIA 91204

T.5931 2 14

SHEAR STRENGTH (cont.)

SPECIMEN	THICKNESS INCHES	MAXIMUM LOAD LBS.	SHEAR STRENGTH PSI
109			
-1	0.273	8,180	9,540
-2	0.295	8,360	9,680
110			
-1	0.276	8,260	9,530
-2	0.265	8,160	9,800
111			
-1	0.275	8,460	9,790
-2	0.277	8,700	10,000
112			
-1	0.244	7,040	9,180
-2	0.240	7,600	10,100
113			
-1	0.250	8,000	10,200
-2	0.241	8,020	10,600
114			
-1	0.242	8,360	11,300
-2	0.239	8,280	11,000
115			
-1	0.249	7,780	9,950
-2	0.238	7,220	9,660
116			
-1	0.240	7,640	10,100
-2	0.242	7,740	10,200
117			
-1	0.248	8,300	10,700
-2	0.240	7,760	10,300
118			
-1	0.246	7,930	10,300
-2	0.251	8,940	11,300
119			
-1	0.248	8,360	10,700
-2	0.248	8,420	10,800
120			
-1	0.251	7,830	9,300
-2	0.240	8,370	11,100

(cont.)

DELSEN corporation
TESTING LABORATORIES
719 W. BROADWAY • GLENDALE CALIFORNIA 91204

T.5931 10 14

DEFORMATION UNDER LOAD
4000 PSI at 122°F. for 24 Hours

SPECIFICATION: ASTM D-621-64

SPECIMEN	WIDTH INCHES	DEPTH INCHES	LENGTH INCHES	DEFORMATION %
Hull #2 & #3				
101-1	0.500	0.501	0.500	0.7
-2	0.501	0.499	0.501	0.7
102-1	0.499	0.497	0.499	0.8
-2	0.503	0.498	0.495	0.8
103-1	0.501	0.500	0.501	0.8
-2	0.494	0.498	0.501	0.8
104-1	0.500	0.500	0.500	0.9
-2	0.500	0.499	0.500	0.8
105-1	0.501	0.501	0.501	0.9
-2	0.495	0.501	0.502	0.8
106-1	0.500	0.500	0.501	1.9
-2	0.501	0.501	0.501	1.9
107-1	0.500	0.499	0.501	1.0
-2	0.501	0.499	0.501	1.0
108-1	0.502	0.503	0.500	0.8
-2	0.500	0.502	0.503	0.8
109-1	0.500	0.502	0.500	1.0
-2	0.502	0.499	0.500	1.0
110-1	0.494	0.500	0.503	0.7
-2	0.495	0.501	0.500	0.7
111-1	0.502	0.502	0.502	0.7
-2	0.503	0.503	0.503	0.7
112-1	0.504	0.502	0.504	2.5
-2	0.505	0.502	0.505	2.5
113-1	0.505	0.507	0.500	0.6
-2	0.521	0.502	0.504	0.6
114-1	0.505	0.502	0.501	0.8
-2	0.503	0.505	0.503	0.8
115-1	0.501	0.505	0.500	1.2
-2	0.504	0.494	0.501	1.2
116-1	0.501	0.499	0.503	0.8
-2	0.503	0.501	0.50[illegible]	0.8

(continued)

RESEARCH AND DEVELOPMENT MANUFACTURING TESTING

DELSEN corporation
TESTING LABORATORIES
719 W. BROADWAY • GLENDALE CALIFORNIA 91204

T.5931 12 14

FLEXURAL STRENGTH & MODULUS
Rate: 0.11"/Minute
Span: 4.000"
Tested at Room Temperature after a Minimum of 88 Hours at 23°C and 50% Relative Humidity

SPECIFICATION: ASTM D-790-66

SPECIMEN	THICKNESS INCHES	WIDTH INCHES	MAX. LOAD LBS.	TYPE OF FAILURE	FLEXURAL STRENGTH PSI	FLEXURAL MODULUS PSI x 10^6
101						
-1	0.276	0.500				4.8
-2	0.279	0.500	107.8	5% Strain	16,600	4.6
102-1	0.278	0.502	106.6	Fracture	16,500	4.8
-2	0.278	0.501	104.3	5% Strain	16,200	4.5
103-1	0.279	0.504	110.2	Fracture	16,900	4.7
-2	0.277	0.500	109.2	5% Strain	17,100	4.8
104-1	0.278	0.496	100.7	Fracture	15,800	4.8
-2	0.276	0.501	95.7	Fracture	15,000	4.8
105-1	0.277	0.503	106.3	5% Strain	16,600	4.9
-2	0.277	0.499	103.8	Fracture	16,300	4.6
106-1	0.278	0.501	100.6	Fracture	15,600	4.5
-2	0.279	0.498	107.3	5% Strain	16,600	4.5
107-1	0.279	0.501	95.9	Fracture	14,800	4.7
-2	0.279	0.503	111.4	5% Strain	17,100	4.7
108-1	0.258	0.501	89.2	5% Strain	16,000	4.6
-2	0.257	0.509	81.6	Fracture	14,600	4.6
109-1	0.279	0.502	108.7	Fracture	16,700	4.5
-2	0.277	0.504	109.5	5% Strain	17,000	4.6
110-1	0.277	0.498	104.1	Fracture	16,300	4.8
-2	0.278	0.502	107.3	5% Strain	16,600	4.6

(cont.)

Figure A-2. Typical Test Data Generated During Testing of Material Properties.

Figure A-3. Control of Bond Strength Quality by Swedlow Inc.

ATTACHMENT #3 - DETERMINATION OF BOND STRENGTH

Swedlow control for Hull No. 3.

Tensile specimens per Federal Test Method Std. No. 406, Method 1011A with the bonded joint located in the center of the reduced area.

Test Temperature: +75°F

Test Speed: 0.050 inches/minute

Specimen Number		Bond Strength (psi)	Type Failure
1 (1)		8000	Bond joint
2 (1)		9150	Bond joint
3 (1)		8540	Bond joint
4 (1)		8830	Bond joint
	Average:	8630	
5 (2)		8240	Bond joint
6 (2)		8320	Bond joint
7 (2)		8080	Bond joint
8 (2)		8330	Bond joint
	Average:	8242	

(1) 0.90 inch thick specimens.

(2) 0.25 inch thick specimens.

Appendix B

NEMO CAPSULES FOR OTHER DEPTHS

The experimental and analytical studies conducted in the development of 66-inch OD x 61-inch ID NEMO capsules with 600-foot operational depth rating (NEMO Model 600) are only indirectly applicable to design of NEMO capsules for other depths. Still, requirements may arise in the future for acrylic plastic capsules either with greater, or lesser operational depth than the NEMO capsule. Although the data generated in the NEMO program will allow to design with a reasonable degree of confidence NEMO capsules for other depths, some additional experimental data will be necessary to confirm the design parameters.

Foreseeing this need, several additional 15-inch diameter capsules of 1.0, 0.75, and 0.25 wall thickness have been built, equipped with polar penetration closures (compressibility mismatch factor of 35) and imploded under short- and long-term hydrostatic loadings. The linear plot of implosion pressure versus time on log-log coordinates permits extrapolating implosion pressures of the few capsules that failed in hours to implosion pressure that occur when the capsules are subjected to lower pressure levels for days, or months (Figure B-1 and Table B-1).

On the basis of implosion data from the additional models and all of the data from the NEMO Model 600 program[1], a plot has been made for predicting the safe* operational depth of acrylic capsules with different t/D ratios (Figure B-2). The recommended t/D ratios for various depths are conservative, as they are based on similar relationship between operational depth, and (1) static fatigue, (2) cyclic fatigue*, (3) short-term implosion, and (4) material strength as was formulated for man-rated NEMO Model 600 capsule. Needless to say, that the compressibility of polar inserts for these capsules must be adjusted to the compressibility of the particular hull so that the compressibility mismatch factor is always less than 35, and preferably less than 20 as otherwise undue stress risers will be present at the insert/acrylic interface.

Although from the theoretical viewpoint, there is no valid reason why 66-inch diameter capsules with as little as 0.250-inch or as much as 8-inch wall thickness cannot be built there are practical limits to the minimum and maximum wall thickness. These practical limits imposed by inherent limitations of the current fabrication process devised for the NEMO type capsules are probably 1.0-inch for the minimum thickness and 5.0 inches for the maximum thickness. The minimum thickness is based on the inability to maintain the required sphericity and wall thickness tolerances in a 66-inch diameter hull of less than 1.0-inch thickness.

*Based on a minimum cyclic life of 1000 dives of 6-hour duration to the operational depth. Dives to a lesser depth are counted as a fraction of the pressure cycle. The fatigue value of dives of lesser or longer duration than 6 hours is computed on the same basis as developed for NEMO capsule[1].

The maximum thickness is based on the inability to thermoform acrylic plate in excess of 5-inch thickness to 33-inch radius of curvature. Unless other fabrication methods for spherical hulls are developed, it appears that the maximum safe operational depth for the thickest (5-inch) 66-inch diameter man-rated acrylic capsules will remain 1350 feet, while for the thinnest (1-inch) 66-inch diameter capsules the maximum safe operational depth will be 150 feet.

Table 3-1. Long-Term Pressurization Tests on 15-inch OD Model Acrylic Plastic Capsules

Specimen No.	ID Inches	Joint	Type of Penetration Closures	Temperature °F	Type of Failure	Sustained Pressure, psi	Duration of Loading, min
22	13	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al-4V)	69	General Implosion	4500	4
23	13	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al-4V)	69	General Implosion	4000	23
24	13	Wide (PS-18 adhesive)	Titanium Plate (Ti 6Al 4V)	71	General Implosion	3500	315
25	13	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al-4V)	70	General Implosion	3000	1575
26	13.5	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al-4V)	71	General Implosion	2900	0.5
27	13.5	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al-4V)	72	General Implosion	2500	6
28	13.5	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al-4V)	70	General Implosion	2000	215
29	13.5	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al-4V)	69	General Implosion	1600	6300
30	14.5	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al-4V)	70	General Implosion	350	0.5
31	14.5	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al 4V)	71	General Implosion	320	6
32	14.5	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al-4V)	70	General Implosion	275	18
33	14.5	Wide (PS-18 adhesive)	Titanium Plate (Ti-6Al-4V)	75	General Implosion	250	8640

NOTE: 1. The polar openings were identical, subtending a 40^{o} spherical angle at the center of the sphere.

2. The penetration closures were of the same thickness and curvature as the acrylic shell.

3. Pressurization rate was 100 psi/minute.

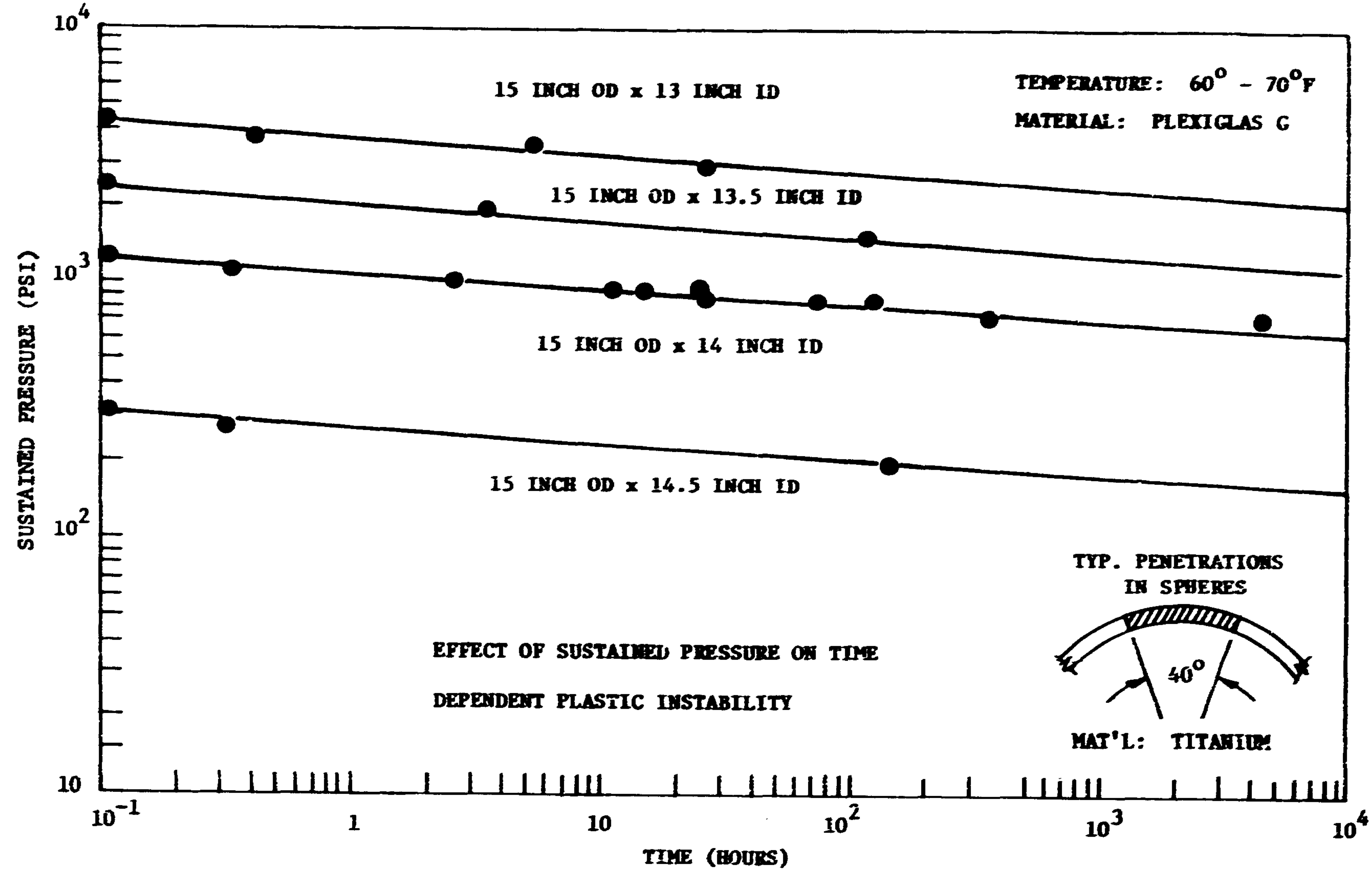


Figure B-1. Implosion pressure of NEMO type acrylic plastic capsules under sustained hydrostatic loading.

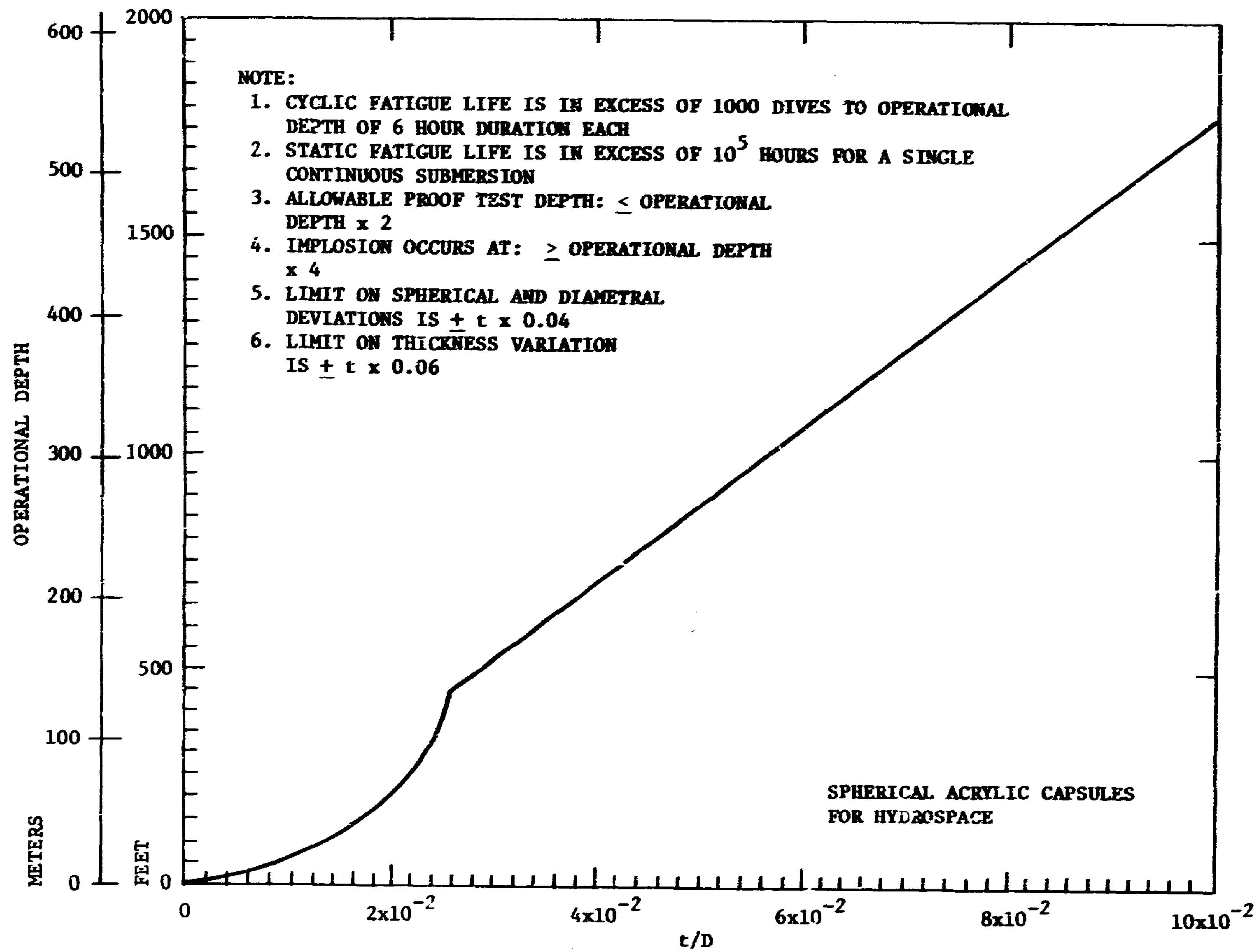


Figure B-2. Recommended operational depths for man-rated submersibles with acrylic pressure hulls of spherical shape.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Civil Engineering Laboratory Port Hueneme, California 93041	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP
3. REPORT TITLE THE SPHERICAL ACRYLIC PRESSURE HULL FOR HYDROSPACE APPLICATION: PART IV - CYCLIC FATIGUE OF NEMO CAPSULE #3	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)	
5. AUTHOR(S) (First name, middle initial, last name) J. D. Stachiw	

6. REPORT DATE October 1970	7a. TOTAL NO OF PAGES 37	7b. NO. OF REFS 3
8a. CONTRACT OR GRANT NO b. PROJECT NO YF 38.535.005.01.006 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) TN-1134 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; it's distribution is unlimited.	
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Facilities Engineering Command

13. ABSTRACT

The 66-inch outside diameter 2.5-inch thick NEMO Model 600 spherical hull #3 has been hydrostatically pressure cycled till fatigue cracks appeared in the acrylic plastic and the top hatch plastically buckled. The plastic buckling of the hatch, fabricated from annealed 4130 alloy steel, took place during simulated repeated dives in the 2080 to 2250 foot depth range. The cracks in the acrylic plastic hull were located in the beveled surface in contact with the metallic polar closures. The first crack was observed only after the hull had been subjected to 993 consecutive pressure cycles, of which 815 cycles were to 1200 feet followed immediately by 178 cycles to 1540 feet. An additional 257 pressure cycles to 2080 foot depth did not implode the pressure hull but only caused the cracks to extend into the hull. The duration of sustained pressure loading in each pressure cycle was approximately 45 minutes followed by 45 minute relaxation period.

The cyclic tests conclusively prove that (1) an adequate cyclic fatigue safety factor exists for NEMO hulls performing, routinely, extended manned dives to 600-foot depth, and that (2) manned proof

Con't'd

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Acrylic resins						
Spheres						
Pressure vessels						
Deep water						
Underwater structures						
Hydrostatic pressure						
Failure						
Buckling						
Implosions						

dives of 1 hour duration to 1200-foot depth can be performed providing the total number of proof test dives does not exceed 100. To prevent plastic buckling of the polar steel closures prior to general implosion of the capsule it is necessary to specify heat treated 4130 steel alloy for the polar penetration closures.